

MYTHS ABOUT SEAWATER INTRUSION IN COASTAL AQUIFERS

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Abstract

Water authorities and users often attribute any observed salinity increase in coastal aquifers to sea water intrusion. Many hydrogeologists expect, as a common situation, the existence of a well-defined "interface" separating freshwater and saltwater that can be easily found by sampling, logging, or using simple geophysical methods. These and other issues are the result of a naive use of physical and chemical principles to over-simplified or wrong aquifer conceptual models in order to try to explain observations that are the result of the complex reality of coastal aquifers. The simple explanations thus obtained can be called "myths" on groundwater behaviour, or "hydromyths", since they respond to a deformed or over-simplified interpretation of real situations that are often based on scarce and occasional observations, or information derived from properties non-directly related with the salinity problem. To redress the interpretation and management deviations derived from these hydromyths, a correct understanding of salinity origin is needed, and also of the water mixing processes occurring in aquifers and in wells, the three-dimensional nature of groundwater flow in aquifers with variable density fluid, and how all these features influence sampling and monitoring. The slow response of groundwater bodies to changes in boundary conditions, the lasting effects of initial conditions, and the important role of fluid density pattern in groundwater flow has to be taken into account. Coastal aquifer management decisions need a good understanding of groundwater behaviour and how it reacts when subject to the stresses to be imposed under the different scenarios. Rules based on incomplete observations and shaped by "hydromyths" may be useful in some cases due to their simplicity, but often they do not yield neither sound decision-making, nor sustainable development and protection of coastal aquifers.

Keywords: coastal aquifers; hydromyths; groundwater management; groundwater flow; salinity pattern.

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Introduction

According to the Webster's New Collegiate Dictionary, the Greek word "mythos", used as "myth" in most western languages, refers to a traditional story of ostensibly historical events that serves to unfold part of the world view of a people or explain a practice, belief, or natural phenomenon. But it also refers to a popular belief or tradition that has grown up around something or someone, and may embody the ideals and institutions of a society or segment of a society. The term has often evolved towards an unfounded or false notion, or a person or thing having only an imaginary or unverifiable existence. This last is the most frequent use of the term.

Consequently a myth can be described as a half-truth derived from real life experiences and observations resulting in deviated interpretations of what really happens due to preconceived ideas, incomplete knowledge or false models of behaviour, or a combination of them. Myths are multiple and widespread, as it is also incomplete and biased our understanding of our world. Myths appear when lay people or non-specialists try or are asked to obtain conclusions, interpretations and guidelines for their activities, by using their own real, or assumed real, experience about things they know partially or poorly.

Often myths are not a serious problem for society, since they allow activity to develop under simple rules producing acceptable inefficiencies and deviations. But in other cases they may lead to too deviated decisions resulting in wrongdoing, at a too high cost for persons and the society. This is the case in which myths have to be redressed, fought and eradicated. This may often mean substituting deeply embodied and widely accepted personal and social norms, considered a traditional and safe behaviour, by new, poorly understood rules, which may look as defying common wisdom to some people.

When myths refer to issues related to hydrology and hydrogeology, they can be called "hydromyths" (Custodio, 2003). Since water is essential to life and it is everywhere in man's activity, hydromyths are widespread and affect many important human activities. Hydromyths often derive from hydrological behaviours that are difficult to be correctly observed due to other overimposed circumstances such as variable weather, climate and land use change, stochastic behaviour of the involved variables, large territories, out of sight path of groundwater.... Thus, it is not rare that hydromyths are numerous and deeply entrenched. They may become one of the most troublesome and difficult to redress and eradicate myths, especially when water resources are scarce and water development is intensive.

In what follows some hydromyths that affect the understanding and use of coastal and small island aquifers and groundwater will be considered. Many of them apply to hydrologists, hydrogeologists, water resources engineers and water managers who study, make decisions and operate in coastal areas.

On the freshwater-saltwater "interface"

The facts: Numerous books, papers and publications show the saline water wedge penetrating inland from below a coastal aquifer (Bear, 1979; Custodio and Llamas, 1976; Custodio and Bruggeman, 1987; Reilly and Goodman, 1985; Cooper at al., 1964; Custodio, 2002a, 2002b). This is a simplified, valid model for many coastal aquifers open to the sea, estuaries and saline lakes, in which groundwater flow discharging

into the coast keeps a distinct saltwater body separated by a relatively sharp contact, or "interface", between the fresh and the saltwater. Many examples can be found in the diverse SWIM publications.

The hydromyth: Many professionals and scientists with some background in hydrogeology tend to accept this appealing and easy model as the universal situation to be expected in almost any coastal aquifer, and try to apply it to any real situation, assuming: a) there is always some kind of "interface" separating fresh water (often equated to drinking or usable water quality) from a saline water body of unspecified characteristics, and b) hydraulic changes in the aquifer result mostly in quasi-horizontal displacement of this "interface".

The real situation: There are numerous and well known cases of existence of a more or less rapid transition between freshwater and saline water in the ground, both in coastal areas and in small islands, in homogeneous formations. But in complex coastal aquifer systems thick transition zones between the two groundwater bodies may develop, and it may happen that the saline water body is of variable concentration and different from that of the sea; also the freshwater body may show already some salinity of climatic or diffusive origin. The saline water body may be quasi-stagnant due to its structural or hydrodynamic circumstances, or may be old marine or saline water contained in low permeability formations (aquitards), and sometimes separated from freshwater bodies in much more permeable and renovated aquifers by a fast change in salinity; diffused salinity is taken away by the dragging along effect of fresh groundwater flow.

Consequences: An incorrect model of the 3-dimensional salinity pattern due to too simplistic assumptions on the existence of a sharp interface which is deduced only from fresh groundwater conditions. As a consequence the assumed aquifer system behaviour under natural circumstances or when it is developed for freshwater -and also for brackish or saline water in some cases- does not respond to reality. Then the existence of mixed water is not explained and the time evolution of water salinity in the aquifers and of the water obtained by means of wells or drains may be fully different. Good examples can be found from classical aquifers as commented in other papers in this and previous SWIMs, as is well documented for The Netherlands (Post, 2004; Oude Essink, 2001).

On the depth to saline water

The facts: In simple cases of sharp interface situations the pressure equilibrium between fresh and saline groundwater measured by the respective heads allows calculating the interface depth if these heads do not change significantly with depth. Heads have to be measured with point boreholes filled respectively with freshwater and saline water of the same density as that in the formation. This situation is a rare one since in most cases only the freshwater head is known. The Badon Ghijben-Herzberg (BGM) principle (Custodio and Llamas, 1976; Custodio and Bruggeman, 1987; Falkland and Custodio, 1991; Lusczynski, 1961) show that the interface depth is $z = \alpha \cdot h$ in which h = freshwater head and $\alpha = \gamma_f / (\gamma_s - \gamma_f)$, γ = specific weight, f = freshwater, s = saline water. This is a simplification in which it is assumed that there are no significant vertical freshwater head gradients, and that the saline water head in the aquifer is zero relative to the datum.

The hydromyth: The depth to the assumed sharp interface is $z = \alpha \cdot h$, and α is typically taken as 40, which derives from $\gamma_f = 1000 \text{ kg m}^{-3}$ and $\gamma_s = 1025 \text{ kg m}^{-3}$ (sea water). When there is information to check this calculation it is often found that groundwater salinity deteriorates at a shallower depth, although in some cases it is still fresh below it. A frequent conclusion is that the BGM principle is erroneous, although it is still applied for calculations due to its simplicity and having no other easy-to-apply rule at hand. In some cases, when the depth at which brackish water starts is known (or it is assumed to be known), the factor α is changed into a new one to try to reproduce these depths; sometimes this seems possible but not always. This procedure is fully empirical, has no clear physical support and does not necessarily hold for other circumstances in the aquifer or for other aquifers. These applications are part of the hydromyth.

The real situation: As commented above the application of the BGM formula with $\alpha = 40$, or some close value after actual water specific weights, assumes there is a sharp interface between i) the saltwater body of marine origin and concentration that is well connected with the sea and its head coincides with mean local sea elevation and ii) the freshwater body without significant vertical head gradients whose head is referred to mean local sea elevation. But in many real cases there is not a sharp interface and then, if the other conditions are respected, the calculated depth falls inside the mixing zone, below the brackish water depth. Also freshwater heads do not necessarily refer to mean local sea level. The datum is at some elevation at some place. Even when open sea level is known in a close-by harbour or coast, the effect of waves, tides and currents may result in a higher or lower local sea level, that may be different from the datum.

Consequences: The indiscriminate application of the BGM principle may lead to deviated, sometimes wrong, descriptions of salinity distribution in the ground. This happens especially when there are thick transition zones, the datum does not coincide with local mean sea level and the saline water bodies potential does not coincide with this local mean sea level due to natural hydrodynamic circumstances or the effect of groundwater development. Major deviations can be expected when the lower boundary of drinking water quality or of useable freshwater is sought. This has a decisive influence on the development of coastal aquifers, and especially of permeable small islands.

On fast changes of groundwater salinity

The facts: Exploitation wells may show fast salinity changes in the pumped groundwater. Also the salinity (or electrical conductivity) distribution along long-screened or multi-screened boreholes may show rapid vertical displacements, accompanied by fast changes in the depth to what appears as an "interface" or different steps of a complex mixing zone. This happens mostly in media with fracture permeability or karstified, but also in more classical heterogeneous porous media.

The hydromyth: The "interface" between freshwater and saline water is able to move vertically a significant distance in a short time (days to months) in response to recharge events and groundwater abstraction or drainage changes.

The interpretation: These fast salinity changes often obey to two main causes. The first one is the relative water head changes along a long-screened or multi-screened borehole as a consequence of recharge

events, groundwater abstraction and even sea level tides and occasional effects. The vertical movement of "interfaces" and salinity distribution inside the borehole is produced in the water inside it, not necessarily in the aquifer, and this allows observing fast displacements inside the borehole. They cannot happen in the ground with actual vertical permeabilities, even under high head gradients. In fractured and karstified media the displacement is dominantly due to relative head changes in the penetrated fractures, which contribute or uptake the relatively small quantities of water needed for the observed displacements. In this case, water salinity in the borehole reflects that of the high hydraulic potential fissures and do not that of low head fissures, which may those mostly contributing to the extracted groundwater. Water salinity in the rock matrix may be fully different. The second cause is upconing due to groundwater abstraction, or the reverse situation under recharge conditions. Abstraction lowers groundwater heads around and below the borehole, well or drain, and consequently vertical upward gradients are created that displace groundwater upwards; density effects tend to reduce, and even may arrest, this movement. Since vertical head gradients may be high and distances relatively small, this may mean changes in a short time (days to weeks) for relatively high vertical permeabilities, and still faster responses when groundwater moves inside fissures or the open space between the borehole casing and the ground. But vertical changes in the ground can be long delayed by continuous low permeability interlayerings. When a borehole allows the hydraulic connexion among different layers with different salinities and water heads, under non-pumped condition, or with small pumping rates, the high hydraulic potential layers yield water that is uptaken by the low potential ones, that in this manner receive water of a different salinity than theirs, that may invade the surroundings depending on the flow conditions. When the borehole is pumped at high rate all layers contribute water. Water coming from the low head layers may be of variable salinity due to previously uptaken water from other layers; the effects may last from minutes to hours or a few days, depending on circumstances.

The consequences: Mistaking fast salinity changes by rapid displacement of the "interface" or saline fronts yields an erroneous explanation of groundwater behaviour and of the response to external effects such as recharge or abstraction. Recharge events may be greatly overestimated, as well as aquifer vertical permeability.

On aquifer "understandability"

The facts: In coastal and small island aquifers large differences in abstracted water salinity among close-by wells and boreholes can be found, even for wells described as "identical". Also abstracted water salinity evolution may be quite different.

The hydromyth: Conspicuous differences in actual water salinity behaviour and evolution of coastal wells in a small area mean a dramatic heterogeneity that renders coastal and small island aquifers too complex to be understood. This precludes effective development and management.

The explanation: Water salinity pattern in the ground in a coastal or island aquifer is three-dimensional (Oude Essink, 2001), and has to be considered at aquifer heterogeneity scale. This means that two close-by wells may be far apart relative to that scale. A horizontal distance of 1 km may be considered small for a study but it may be greater than the horizontal heterogeneity scale, and much greater than the vertical

scale. The 3-dimensional behaviour is a key consideration. Thus, small differences in two close-by "identical" wells may be the cause of significant changes. Such are the depth of the borehole, the depth and length of the screens, the effective sealing and grouting of the annulus, the local variations of aquifer thickness, permeability, development and clogging, other features of gravel packs, defects in tube welding, corrosion effects..... This means the characterisation is not enough to establish the "identity" of two situations. But given enough horizontal and vertical information, observed salinity differences can be explained.

The consequences: Considering an aquifer as too complex to define a workable conceptual model may mean downplaying the possibility to understand it and carrying out a reasonable and sustainable development. This puts aside the possibility of evaluating the impact of activities that affect the aquifers, such as recharge modifications, drainage by civil works, groundwater development, or drilling through the aquitards that delay vertical salinity displacement.

On sustainability of coastal aquifer development

The facts: The development of a coastal aquifer, even with low intensity exploitation, often involve some wells presenting excessive salinity from the start or after some time of operation, and the drying up or salinity increase of low altitude springs and wetlands. But in other cases, after many years of intensive development, including areas subject to head drawdown, even below sea level, the salinity of coastal aquifers continues to be invariably fresh.

The hydromyth: The development of an aquifer, and especially of a coastal aquifer, means depletion or salinized wells after some time. Other hydromyth is just the opposite: Coastal aquifers can be exploited without salinization danger when there is a tight, effective isolation from the sea.

The explanation: In coastal and small island aquifers there are saline water wedges intruding from the sea and possibly other brackish/saline groundwater bodies. It is not rare that some exploitation wells become affected by salinity if they are not carefully placed and installed, or get some contamination by upconing or lateral displacement of salinity fronts. This is normal behaviour since coastal aquifer development means shrinking freshwater bodies in the ground. Some salinity problems in wells, low altitude springs and wetlands, and drains, do not mean that a part -a large part- of the system cannot be sustainably used. Once defined what is the sustainable use, some development rules can be found that meet the imposed constraints. In the case of an assumed coastal aquifer isolation from the sea, besides a good geological/hydrogeological study that can not be based in incomplete or assumed geological data, the time factor has to be considered. Groundwater moves slowly and salinization may imply long distance displacements of the saline front through low permeability formations, and this means, a very long time, that may produce a false security feeling. The existence of preferential paths (buried valleys, fractures and open faults, more permeable interlayers) may allow unexpected, sudden salinity increases in some areas after a long time without problems.

Consequences: Both extreme situations may induce coastal or small island aquifer groundwater resources mismanagement. In the case where some salinization problems are observed, the fact of applying a local

result to the whole system, downplays the role of the aquifer system as a reliable source of freshwater for normal and for emergency supply. In the case of assuming an effective isolation of the aquifer from the sea, when the aquifer sustainable development possibilities are exceeded there is the risk of an unexpected water salinity degradation before other alternative source of groundwater is made available. The false feeling of security often downplay the role of adequate monitoring as too expensive and irrelevant, while it should be the contrary.

On the origin of salinity

The facts: The coastal area and the small island environment are prone to show groundwater salinity problems, both under undisturbed and under disturbed conditions (Falkland and Custodio, 1991).

The hydromyth: Seawater is the origin of water salinity and it can be reduced by preventing the easy hydraulic contact between aquifers and the sea.

The explanation: The coastal area is not only the contact between land and sea water but also the final discharge area of the continental or island water system, and a zone affected by seawater spray and airborne marine salts, especially when the sea is rough and winds come from the sea. This affects recharge salinity in the coastal area; in arid environment it may become brackish (Herrera and Custodio, 2002). Also water evaporation surfaces (wetlands, marshes, lagoons) may yield saline water, and even brines, which may enter the ground, sometimes favoured by the increased water density. Similar considerations can be adduced for the sometimes saline return irrigation flows (Llamas and Custodio, 2003; Milnes and Renard, 2004). Saline groundwater bodies in the ground are not necessarily related with present seawater but may be old marine water, more or less modified by chemical processes in the ground, old surface-generated brines, and even the result of ground salt dissolution. The abstraction of brackish or saline water from the ground may be the origin of saline water infiltration in the surroundings, or in other places when it is transported through the territory; this may contribute to salinity problems in some areas. The wide variety of saline sources means that establishing the origin of salinity in complex aquifer systems is often not an easy task. Besides good geologic and hydrodynamic understanding of the system, detailed hydrogeochemical and isotopic studies are needed.

Consequences: The incorrect identification of salinity sources not only leads to inappropriate aquifer system conceptual models but to deviated protection measures, inadequate well construction and operation rules, and ineffective management. This is one of the most difficult aspects of sound coastal and small island aquifer management.

On saline water development in coastal areas

The facts: Brackish and saline water development in coastal areas may be used for industrial cooling (old freshwater wells, or wells constructed for this purpose), for supplying membrane desalination plants, and for feeding fish-breeding factories.

The hydromyth: Abstraction of saline water from coastal aquifers has to be avoided since this increase salinity problems by attracting additional saline water.

The behaviour: The abstraction of saline water decreases its hydraulic potential, which favours freshwater volume expansion in the aquifer. In this respect this may be a favourable circumstance for protection against seawater intrusion (Sherif and Hanza, 2001), and this has been an important factor for the management of the Llobregat delta (Custodio and Bruggeman, 1987). But in many cases what is abstracted is a mixture of seawater (or original saline water) and freshwater, depending on well design and operation. This means a consumption of freshwater that has to be considered for computing heads and the aquifer freshwater balance. Salinity problems may appear if used brackish or saline water, or desalination brines, are inadequately disposed or there are failures that produce infiltration of these waters (disposal into the ground, leakages, accidental outflows) in freshwater parts of the aquifer system.

The consequences: Forbidding or limiting brackish or saline water development in a coastal aquifer may imply losing an opportunity for salinity penetration control, although with some increased consumption of freshwater. An adequate construction and operation of wells reduce freshwater uptake. Safe disposal of used water is needed to avoid saline water recharge.

On deep freshwater and discharge into the sea

The facts: In some cases there are deep aquifers containing freshwater, even below saline water aquifers.

The hydromyth: In coastal aquifers, below saline water aquifers, other freshwater containing aquifers can be expected; deep wells are recommended. Otherwise continental freshwater resources may be lost to the sea in submarine outflows.

The explanation: Deep freshwater aquifers are possible under some circumstances (Zekster et al., 1973; Buddemeier, 1996; Burnett et al., 2001; Young, 1996; Urish and Ozbilgin, 1989). This is the case of confined layers recharged at high altitude and with some flow, or when paleowaters have been preserved under no significant flow conditions (Edmunds and Milne, 2001; Kooi and Groen, 2001). This is not the common situation, in which salinity increases downward due to the encroaching saline wedges or the entrapment of old marine waters in closed formations or in aquitards that diffuse salts to the aquifers. In flat areas deep saline groundwaters and even brines are commonly found. The discharge of freshwater into the sea from a deep aquifer needs not only some direct or indirect hydrogeological connection, but enough head to overcome the denser seawater column at the submarine outlet points or surfaces, and this only happens under favourable circumstances and in relatively high relief landscapes.

The consequences: The hydromyth is the origin of many unfilled expectatives, at a high cost. Non-specialists are induced to think that coastal aquifers are unreliable and mysterious, thus downplaying their important role to supply human needs. Also submarine outflows of freshwater are not necessarily a loss because they play an ecological role (Johannes, 1980).

On coastal aquifer similarity

The facts: Coastal and small island aquifer flow and salinity pattern are the result of many local circumstances that make unique each aquifer and aquifer system. This does not appear at a first sight but after a detailed knowledge. Geological and hydrogeological maps tend to present aquifer types (deltas, dune belts, alluvial fans, carbonate formations, vulcanites, etc.) which present apparent similarities.

The hydromyth: Two coastal or island aquifers with a similar geological-hydrogeological structure behave similarly, even if of different size. This means that the knowledge gained in one of them can be extrapolated to the other.

The explanation: Present and past hydrodynamic conditions may play a dominant role in water heads, and they deeply influence the salinity pattern. Also small differences in permeability, continuity of formations, and degree of heterogeneity may mean a significant difference. Deep confined aquifers which are open to the sea at the downflow end may be flushed out of saline water if the water head at the recharge area is high enough during a sufficient time, but not when heads are low, as happens in very flat areas.

The consequences: Deducing the salinity conditions of coastal and small island aquifers by comparing with other similar, known situations may lead to wrong conclusions if hydrodynamic conditions are not taken into account besides geological ones, and there is some information to support what is deduced from the assumed similarity.

References

- BEAR, J. (1979). *Hydraulics of groundwater*. Mc Graw Hill, New York: 1-379
- BUDEMEIER, R.W. ed. (1996). Groundwater discharge in the coastal zone. *Proc. Intern. Symp. LOICZ/R&S/96-8*, Texel, NL: 1-179.
- BURNETT, W.C.; TANIGUCHI, M. and OBERDORFER, J. (2001). Measurement and significance of the direct discharge of groundwater into the coastal zone. *J. Sea Research*, 46 (2): 109-116.
- COOPER, H.H. JR., KOHOUT, F.A., HARRY, H.R. and GLOBER, R.E. (1964). Sea water in coastal aquifers. U.S. *Geological Survey Water-Supply Paper* 1613-c, Washington D.C.: 1-82
- CUSTODIO, E. (2002a). Coastal aquifers as important natural hydrogeological structures. *Groundwater and Human Development* (E. BOCANEGRA, D. MARTÍNEZ and H. MASSONE, eds.). Univ. Mar del Plata: 1905-1918.
- CUSTODIO, E. (2002b). Aquifer overexploitation, what does it mean? *Hydrogeology Journal*, 10 (2): 254-277.
- CUSTODIO, E. (2003). Realities and myths of intensive aquifer development. *Aquifer Vulnerability and Risk* (Intern. Workshop). Salamanca, Guanajuato (R. RAMÍREZ, CIVITA and M. DE MARIO, eds.). 2: 207-222.
- CUSTODIO, E. and BRUGGEMAN, G.A. (1987). Groundwater problems in coastal areas. UNESCO-IHP, *Studies and Reports in Hydrology*, 45. Paris: 1-576.
- CUSTODIO, E. and LLAMAS, M.R. (eds). (1976). *Hidrología subterránea*. Ed. Omega. Barcelona, 2 vols: 1-2350.
- EDMUNDS, W.M. and MILNE, C.J. (2001). Palaeowaters in coastal Europe: evolution of groundwater since the Late Pleistocene. *Geological Society of London, Special Publication* 189: 1-630.
- FALKLAND, A. and CUSTODIO, E. (1991). Guide on the hydrology of small islands. UNESCO-IHP. *Studies and Reports in Hydrology*, 49. Paris: 1-435.

- HERRERA, Ch. and CUSTODIO, E. (2002). Old marine water in Fuerteventura island deep formations. *Proc. 17th Salt Water Intrusion Meeting*. Delft University of Technology: 481-488.
- JOHANNES, R.E. (1980). The ecological significance of the submarine discharge of groundwater. *Mar. Ecol. Prog. Ser.*, 3: 365-373.
- KOOI, H. and GROEN, J. (2001). Offshore continuation of coastal groundwater systems: predictions using sharp interface approximations and variable-density flow modeling. *J. Hydrology*, 246: 19-35.
- LUSCZYNSKI, N.J. (1961). Head and flow of groundwater of variable density. *Journal of Geophysical Research*, 66 (2): 4247-4256.
- LLAMAS, M.R. and CUSTODIO, E. (eds). (2003). *Intensive use of groundwater: challenges and opportunities*. Balkema. Lisse: 1-471.
- MILNES, E. and RENARD, P. (2004). The problem of salt recycling and seawater intrusion in coastal irrigated plains: an example from the Kiti aquifer (Southern Cyprus). *J. Hydrol.*, 288: 327-343.
- OUDE ESSINK, G.H.P. (2001). Salt water intrusion in a three-dimensional groundwater system in The Netherlands: a numerical study. *Transport in Porous Media*. 43 (1): 137-158.
- POST, V. (2004). *Groundwater salinization processes in the coastal area of the Netherlands due to transgressions during the Holocene*. Vrije Universiteit, Amsterdam (Doctoral thesis): 1-138.
- REILLY, T.E. and GOODMAN, A.S. (1985). Quantitative analysis of saltwater-freshwater relationships in groundwater systems - a historical perspective. *J. Hydrology*, 80: 125-160.
- SHERIF, M. and HANZA, K. (2001). Mitigation of seawater intrusion by pumping brackish water. *Transport in Porous Media*. 43: 29-44.
- URISH D.W. and OZBILGIN, M. (1989). The coastal ground-water boundary. *Ground Water*, 26: 267-287.
- YOUNG, P.L. (1996). Submarine groundwater discharge. *Nature*, 382:121-122.
- ZEKSTER, I.S.; IVANOV, V.A. and MESKHETELI, A.V. (1973). The problem of direct groundwater discharge to the seas. *J. Hydrology*, 20: 1-36.