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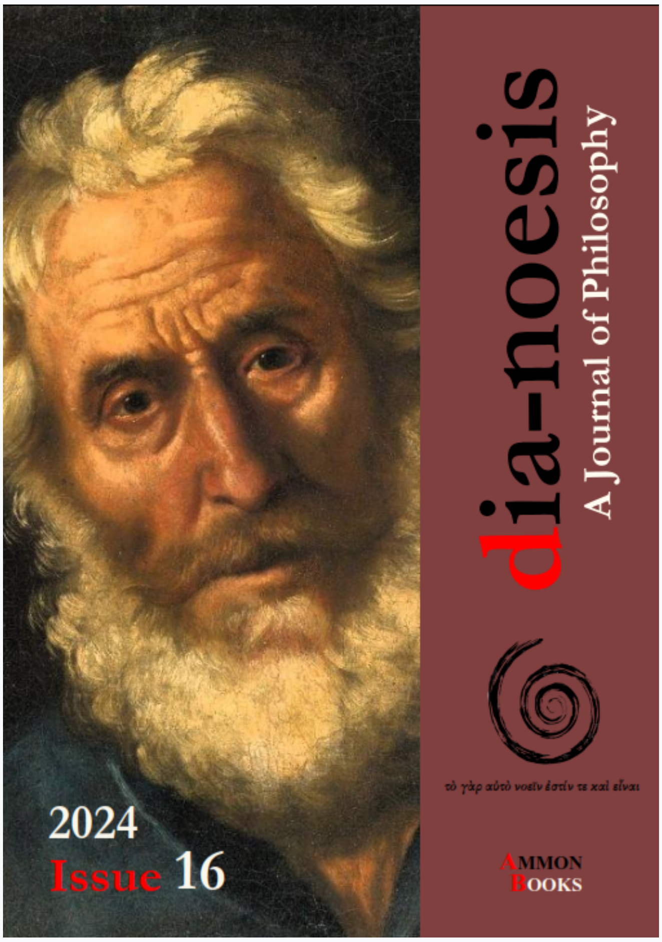

Rivers, Tides and Currents

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Rivers, Tides and Currents
A Note on The History of Ancient Hydrology

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Abstract

Ideally, natural scientific theories, even the most speculative ones, need empirical confirmation, which, however, is not always possible and, even when achieved, cannot always be correctly interpreted. Moreover, as practical experience accumulates, the investigators of nature with more reason reject the least successful theories, and obtain new confirmations for the most successful ones. This is the way science works, both in modern times and in antiquity. Applied to the history of ancient hydrology, this means that we can trace the development of natural scientific ideas from early thinkers such as Thales, Empedocles, Diogenes of Apollonia, Plato,v and Aristotle, to the Roman and early Byzantine period, represented by encyclopaedic authors such as Posidonius, Seneca, Strabo, and Alexander of Aphrodisias. As a result, we will see not only the evolution of natural scientific ideas, but also, in some cases, we will be able to assess the methodological and empirical acceptability of the physical ideas of late antiquity, which emerged as a result of the trial and error of ancient naturalists and their long reflection on the riddles of nature. In general, the article is devoted to the ancient concept of the circulation of water in nature. In its first part special attention is given to an analogy between natural phenomena and the processes occurring in living organisms, common to our philosophers of nature, as well as the peculiarities of their interpretation of the theory of mutual transformation of the elements. We note the place of the method of analogy in their observations and theoretical constructions. The second part of the article is dedicated to tides and sea currents. We look at the history of their observation in antiquity as well as alternative theories, designed to explain their nature. Special attention is given to ancient explanation of the phenomenon of the periodical change of the stream in Euripus' channel (Chalkida, Greece).

Keywords: ancient science, ancient astronomy, empirical method, elements, the circulation of water, seas, currents, tides, Plato, Aristotle, Posidonius, Seneca, Alexander of Aphrodisias.

Rivers and Seas

All the physical processes are organic because Nature resembles living organisms. This general attitude is shared by many philosophers of nature at least from the time of Empedocles. The idea is clearly expressed by Seneca (*Natural questions* [hereafter NQ] 3.14.3, tr. H. M. Hine), who says that the sea "…has its own veins from which it is renewed and forms tides."

This analogy is further developed in the subsequent paragraphs (3.15.1–16.1). Nature designed the earth analogously to our bodies: it supplied its surface with veins, which contain "blood," and arteries, which contain "air". The blood of the earth is water; the air of the earth is its exhalations. Moreover, as our body contains various humors, some beneficial, some malignant, in the earth "hardening" moisture creates metals, while "decayed" moisture is responsible for appearance of asphalt, naphtha, and similar substances. As in organic bodies these liquids are spoiled when shaken, exhausted, frozen, overheated, contaminated with dangerous admixtures, such as sulphur, etc. Some of these processes are long-lasting indeed, some are extremely short-lived. Periodically a sudden "purification" and "healing" occur:

> "But why are some springs full for six hours and dry for six?" ...Just as quartan fever turns up on the hour, just as gout keeps to time, just as menstruation sticks to a set day if nothing intervenes, just as childbirth is ready to happen in the right month, in just the same way waters have intervals at which they withdraw and return (Seneca, NQ 3.16.1).[1]

[1] In a similar manner Alexander of Aphrodisias in his *Natural questions* (2.23) refers to the previous students of nature, such as Diogenes of Apollonia, to the effect that even "…all metals both emit a certain moisture (ἰκμάδα) from themselves and draw it in from outside, the ones more, the others less, and that copper and iron emit the most…" (A 33 DK, T 36 Laks; cf. Empedocles, fr. 680 Bollack). In a similar manner, according to Diogenes the spontaneous births of plants occur when "the water putrefies and takes on a certain mixture with regard to the earth" (A 32 DK, T 34 Laks; ap. Theophrastus, *History of Plants* 3.1.4).

Just as blood flows from a torn vein until the wound leaks out or the wound heals, so sources, pure or containing impurities, flow out of the gaps in the ground until the gap closes (for example, due to silting). Then the gaps are tightened like a scar. Sometimes devastated veins are again filled with water, borrowing it from another place, or are restored by themselves, "gathering strength" (just as the body heals itself). What is the mechanism for such a recovery? It turns out that the earth, being diluted ("rarefied"), turns into a liquid, and the air, condensing, becomes water just as it happens in clouds (Seneca, NQ 3.15.6–7). Is it possible? Yes. If air comes from water, water from air, fire from air, air from fire, so why should water not come from the earth? – asks Seneca (id. 3.10.1). In general, "everything arises from everything": the basis of the world is four elements capable of turning into each other. Water and earth are related elements, both heavy, dense and pushed to the very bottom of the universe. Moreover, all elements have already been mixed into what they can turn into. So, the air already contains the heat inherent in the fire, and if this heat is taken away from the air, the latter will harden, condense and turn into water. In the same way, the earth can produce air and moisture, but it itself is never deprived of them. Thales considered water "the most powerful element" and the beginning of everything. However, the end of everything, Seneca develops the Stoic teaching, is fire. The fire that fills the world gradually weakens and, extinguished, gives rise to moisture, which becomes the "hope of a future world" (3.13.1). "Nothing is exhausted if it returns to itself," which is why there are still deep rivers and deep seas. The nature carefully preserves a balance (3.10.3).

So, natural phenomena are mutually consistent and due to certain reasons. When the balance of elements and processes is disturbed, various diseases and cataclysms occur. We hear about this from many philosophers, at least since Aristotle. In addition, observations made in one area can be extended by analogy to the adjacent. Earthquake, for example, is similar to urination or convulsions: the earth, like our body, is pierced by some kind of tremor caused by the movement of an exhalation (*pneuma,* Aristotle, *Meteorology* 366b18-30); the land and the sea, "according to ancient theologians," have roots (353a35); the sea is the sweat of the earth heated by the sun, therefore it is salty (353b12, from Empedocles,[2] cf. 350a3 "the upper layers of the earth seem to be sweating"); and, in general, the earth acts as a common stomach for plants, and the stomach of animals is an internal replacement of the earth (Aristotle, *On animal parts* 650a21 and 678a31); "the interior parts of the earth have their maturity and age, like the bodies of plants and animals", though not all at once, but in parts, the sun dries them and ages, and the moisture revives (*Meteorology* 351a27 ff.). And this reverts us to the aforementioned statement that water is the beginning of the world and fire is its end (Seneca, NQ 3.13.2).

Examples can be easily multiplied and some of them have been popular since the times of the first philosophers of nature. It is important that, along with direct observations of natural phenomena, suitable analogies can be used to explain their mechanism, especially in cases where direct observation is difficult or impossible (cf., for instance, *Meteorology* 369a20). It is noteworthy that although in many cases the analogy can replace the definition (*Metaphysics* 1048a35) Aristotle nevertheless does not seek to make the argument by analogy a part of the scientific method.[3] The latter should be based on a hypothesis (for example, this of dry and wet exhalations, prominent in his *Meteorology*), confirming observations of the phenomena in question, and, whenever possible in empirical sciences, rigorous proof. So, the analogies only complement the empirical data and make it possible to clearly explain the essence of unusual or rare phenomena that cannot be directly investigated. In some cases, we can talk about experimental verification. For example, Aristotle seeks to explain the salinity of the seawater in the same way as other "meteorological" phenomena, using its main hypothesis of wet and dry

[2] Empedocles, fr. 395 Bollack (31 A 25 и 66 B 55 DK); cf. Democritus, 68 A 99 and Antiphon 87 B 32.

[3] For details, cf. Freeland 1990. A more general picture is found in Taub 2003. Aristotle's method is well contrasted with this of Theophrastus' meteorological and, in general, scientific works in Daiber 1992 and Fortenbaugh et al. 1992.

exhalations. Dry exhalation contains residues that appear because of the natural process of growth ("like waste that collects in the bladder").[4] It is these "earthy" remnants found in seawater that are responsible for its salinity. How to check it? One can, for example, strain the water through the ashes. As a result, it becomes bitter. For the same reason, salt deposits form on the pots (*Meteorology* 357b1, 358a5 ff.). The fact that the salinity is due to some admixture can be confirmed by experiments. If one makes a vessel of wax, closes it tightly and places it in seawater, the moisture that has leaked through the wax walls will be fresh. The presence of certain impurities in seawater also explains why it is heavier than fresh water; therefore, overloaded ships coming from the sea can sink in freshwater rivers. In Palestine, there is a lake where people and pack animals do not sink; indeed, if we take very salty water, then an egg sinking in ordinary water, will not sink in it (ibid 359a1 ff.), etc.

The experience with the egg is quite correct, however, the wax vessel will not work as a wonderful desalination plant: the water will not penetrate through its walls and the small amount of liquid inside clearly accumulates due to condensation. Nevertheless, Aristotle mentions this "experiment" in the *History of Animals* (590a22), and after him this mistake is repeated by other ancient authors, in particular Pliny (*Natural History* 31.37.70). We see that our natural philosophers strive to confirm their theoretical premises with empirical data, but it is clear that they do not

[4] This place is interesting from a methodological point of view. Immediately before this observation, Aristotle criticizes Empedocles' poetic expression "the sea is the sweat of the earth," noting that such metaphors are inappropriate when exploring nature (357a25). From Aristotle's point of view his predecessor took the first step in understanding the true nature of the phenomenon, but he did not have a proper theory. Therefore, Aristotle himself, first, immediately develops the analogy of Empedocles: seawater is salty for the same reason as urine in the organism of a living being. The pure water consumed by the body is mixed with various substances, which are then taken out with urine and sweat. In the same way, in the seawater, "earth" is mixed in with "moisture", which can be observed on the vessel walls in the form of a salt deposit (ibid 357a32 ff. and 358a5 ff.). Secondly, he further suggests the mechanism of this process based on his theory of two exhalations.

always verify the information transmitted, simply by collecting standard examples and opinions of their predecessors expressed on a given occasion.

Let us return to the hydrological observations of Seneca. It has long been observed that a certain water cycle occurs in nature: the moisture that rises due to evaporation falls in the form of precipitation and then a part of it seeps into the ground, and the other part flows over the surface and forms surface water bodies. So, the earth seems to be "receives back all the water it has discharged," says Seneca (NQ 3.5). Therefore, where it rarely rains, there are few rivers, as is observed in the deserts. However, not everything is so simple (3.7). Every farmer knows that after a rain the soil gets wet no more than a dozen feet, so that all moisture remains at the surface and rain water cannot feed all water flows without exception. On the contrary, it is known that water also flows out of rocks, often at a high altitude, and similar streams flow over rocky terrain, so that water cannot seep inside. Finally, it is known that even in the driest places deep wells contain abundant water. This means that the water cycle is observed under the ground: the sea "secretly" penetrates the earth and invisibly returns from it, on the way back under pressure, filtering through the thickness of the earth. It is through this process, in full agreement with Aristotle (see above), that water loses bitterness and becomes fresh (3.5), while retaining, however, some impurities that are different in taste and often useful and healing (3.1.2).

Water flows downwards, sometimes the wind drives it upwards (3.3), sometimes it rises from the ground under pressure (3.7.4), but in general, everything looks as if the sea does not feel the influx of rivers, and the land does not feels their outflow, as if there are always some "hidden reserves" of water, occupying certain underground reservoirs, "as broad as the ocean and its gulfs in our world, or rather all the broader, because deep down the earth spreads out further" (3.4, 3.8–9). In addition, underground, there are vast voids filled with heavy and stagnant air, which condenses into water (3.9), and the earth, thinning, turns into a moist substance, because, I recall, elements can turn into each other due to the processes of condensation / rarefication and heating / cooling (3.10.5).[5]

Another natural process leading to the water cycle, Seneca describes with reference to Diogenes of Apollonia:

> "The sun attracts to itself the moisture that the dried-out land draws from the sea and also from other waters. But it cannot happen that the land is dry in one place and overflows in another: for the whole is perforated and one part communicates with another, and the dry parts take from the moist ones. Otherwise, if the earth received nothing, it would have completely dried up. Thus, the sun attracts [scil. water] from everywhere, but [scil. especially] from those regions that it most oppresses: these are the southerly ones. When the earth has become completely dried up, it attracts more moisture to itself: just as in lanterns the oil flows to the place where it is burning, so too water flows to where the force of heat and of the burning earth summons it. From where then does the latter attract it? Evidently from those regions where it is always winter: the northerly ones constantly overflow (that is why the Black Sea runs continuously in a rapid stream into the lower sea [i.e., the Mediterranean] and does not ebb and flow with alternating tides like other seas, but always flows swiftly in the same direction). For if what each one lacks were not restored to it and the excess were not discharged thanks to these passages, then everything would already be either dry or overflowing." (Seneca, NQ 4a.2.28–29, tr. A. Laks and G. Most).[6]

Unfortunately, the rest of this book of the treatise (on the flooding of the Nile) has not survived, but in conclusion Seneca expresses some doubts about Diogenes' theory: for example,

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[5] Cf. Aristotle, *Meteorology* 349b20 ff.

[6] Having described this physical process, Seneca attaches to it the opinion of Diogenes on the flooding of the Nile, identical to that transmitted by John Lydus (must be borrowing from Seneca). Something similar is also repeated in a very spoiled text, a 13th cent. Latin translation, attributed to Aristotle (Fr. 248, "On the Flooding of the Nile", p. 192, 22–29 Rose).

why do droughts sometimes occur if, according to the described mechanism, the most heated parts of the earth pull the moisture most strongly?

Anyway, the described dynamic processes provide a natural balance and everything happens according to the established order: "Winter never goes astray; summer heats up at the right time; the change to autumn and spring occurs at the usual point; solstices and equinoxes alike recur on the right day" (3.16.3). But this balance is very fragile: Nature need only slightly alter the existing course of things and the world would perish (ibid. 3.27.3). What if, for example, immense rain will pour or a huge tidal wave rises from the sea?

What determines global changes in the world order? In order to approach this problem Aristotle addressed the question of the origin of the sea. The theologians, he says, invented some "sources" of land and sea, its beginnings and ends (cf. Hesiod, *Theogony*, 282, 785–792), but "those who were wise with human wisdom" strived to discover its true origins. In the beginning the whole region of the earth was "surrounded by moisture," and then the part of the water, dried up by the sun, turned into evaporation, while the remaining part formed the sea. This means that once time will come when the sea will dry up altogether. Next, he repeats the opinions of the philosophers about the salinity of the sea (353b7–16). As already noted, Empedocles (fr. 395 Bollack; 31 A 25 and 66 B 55 DK), Democritus (68 A 99) and Antiphon (87 B 32) called the sea 'the sweat of the earth'. Another opinion (aforementioned analogy with ashes) is found in Xenophanes (21 A 33), Anaxagoras (59 A 90), and Metrodorus (70 A 19). Alexander of Aphrodisias supplements the first of these opinions with the theory of Diogenes, who proposes a more detailed mechanism. Some philosophers, he says, indeed regard the sea as "a remnant of primary moisture," which, Alexander explains, is the cause of winds (πνεύματα) and the retrograde motion of the sun and the moon ("since they make turns as a result of this exhalation, turning around those places where there is a source of supplying them with exhalation"),

> "... and that part [of the primary moisture] which remains in the hollows of the earth is the sea, so the sea is constantly decreasing, drying up under the action of the sun, and in the end will once become dry land. This opinion, as reported by Theophrastus, was held by Anaximander and Diogenes. Diogenes, moreover, explains the reason for the salinity of the sea by the fact that the sun evaporates fresh water, and the remaining water turns out to be salty (due to remaining residue)"[7] (A 17 DK, T 32 Laks; Alexander of Aphrodisias, Commentary on Aristotle's *Meteorology*, *ad* 353a32; p. 67, 1–14 Hayduck).

The world as a whole is eternal, but its individual parts are subject to change – "the interior parts of the earth have their maturity and age, like the bodies of plants and animals" (*Meteorology* 351a26–27), therefore, those speaking about the variability of the universe, according to Aristotle, right and wrong simultaneously (352a23 ff.). They are right that some changes in the universe actually take place, but they are mistaken in making a conclusion about the variability of the universe as a whole based on the observed changes in its individual parts. The universe is subject to certain cycles and the earth (its insignificant part) undergoes not only a change of seasons, but also, as it is believed, more global changes. So, a "great winter" may come or unusually prolonged rains can be shed, but all this will in no way change the whole earth and the movement of the luminaries. As an example, Aristotle mentions the mythical "deluge in the time of Deucalion", noting that he nevertheless wore a local character and affected the Greek world only (ibid 352a30), and other more real climatic changes. Some areas, for example, Egypt, are gradually becoming the land and some of its parts that once bloomed are depleted (351b35 ff.); Mycenaean land was flourishing during the Trojan War; on the contrary, the once-swampy land of Argos dried out a little and became more livable, etc. (352a9 ff.). All these changes occur gradually, therefore it is difficult

[7] Hippocrates is of the same opinion in *On Airs, Waters and Places* (ch. 8; CMG I, 1, p. 62, 11) as well as Porphyry in his *Homeric Questions* (*ad* the *Iliad* 11.53. 54), p. 161 Schrader).

to witness them, since not only human life is short in comparison with them, but also the time allotted to whole nations. Even when migrating from place to place, the tribes do it so gradually that the memory of the movements, and how the place where the first settlers came looked like erased from the people's memory (351b9 ff.).

Still, can the sea dry out? According to Diogenes, never. Aristotle explicitly criticizes this position in 352a20 and 355a22-25 (and Alexander once again mentions it in his commentary: pp. 73, 21 ff.). However, observations show that the coastline may change due to river sediments (351b5 ff.). Libya is located below the coast, which means that this plain was once filled with water and gradually dried. A similar process is observed in the lake Maeotis, which has become noticeably smaller over the past sixty years. One can see with his own eyes the shoals on the Bosporus, which can also dry out over time (352b20 ff.), etc. So, it appears that land and sea can generally change places and where there was a sea, land will emerge over time and vice versa (351a20 ff).

And yet, according to Aristotle, the main contribution to the water cycle is the loss of water from sea spaces, because a large surface is needed for efficient and fast evaporation (355b25 ff.). In this sense, the sea is rather the "end" of the waters than its beginning: the light and fresh water evaporates from it, while the heavy and salty remains. Something similar, notes Aristotle, occurs in the body of animals that absorb fresh liquid, and secrete saline, containing all the liquid waste (355a5 ff.).[8]

It is known that periodically the floods do occur in different parts of the world, but what processes, asks Seneca, can be responsible for a real flood, which would swallow the whole earth? This seems unlikely, but still even a slight disturbance of the natural balance is capable, according to Seneca, produce catastrophic results: "when that inevitable moment arrives, fate

[8] On the contrary, it is unreasonable that Plato in the *Phaedo* (111c ff.) says about underground rivers that are supposedly interconnected by channels leading to Tartarus. Aristotle does not deny the existence of groundwater, but this theory seems fantastic to him (*Meteorology* 356a ff.). Plato himself must have talked about underground rivers in a metaphorical sense, while later authors found this colorful idea attractive.

sets in motion many causes at once; for such a change cannot occur without the world being shaken" (NQ 3.27.3). Because of the incessant rains, the earth will soften and loosen, snow will accumulate over the mountaintops (3.27.7) and a giant tidal wave will rise from the sea (3.28.2–4).

Currents and Tides

Nature is like a living organism. This general attitude was shared by many ancient natural philosophers. It is also the basis of ancient hydrology.[9] This idea, of course, is very metaphysical, but the conclusions that were drawn on its basis allowed ancient natural philosophers not only to offer an explanation for the various processes of the water cycle in the atmosphere and under the earth, but also to make assumptions about the general causes of the movement of water in the ocean. If nature is a living organism, then its processes must somehow co-ordinate with each other to ensure renewal and growth, without which there is no life. The circulation of 'juices' sustains, according to the Hippocratic physicians, organic life, from plant to man. If nature is organized in the same way, then on a global scale its existence must also be sustained by the movement of waters. Examples are easily found. Thus, sea tides, according to Seneca, are caused by the filling and emptying of underground 'veins' (NQ 3.14.3). It is remarkable that this 'biological' theory is combined in Seneca with the correct 'astronomical' explanation of the origin of sea tides, already well known at that time. Such a mention of many causes is generally characteristic of ancient authors, seeking to approach the same phenomenon from different sides, taking into account the most diverse opinions of predecessors. Thus, Seneca writes:

[9] "The sea is similar to living beings and like them breathes in and out" (Strabo, *Geography* 1.2.8). It is noteworthy that the movement of the seabed is also similar to breathing, at least so believed the Peripatetic Strato of Lampsacus, who, according to Strabo (*Geography* 1.3.5), thought that "the seabed rises and falls, and together with it the sea rises and falls". For details, cf. Fortenbaugh, Desclos 2010.

> "As of all the tides that occur during the equinox, the greatest is that which falls on the coincidence of the sun and the moon, so the tide sent by the sea to conquer the land will be much more powerful than the strongest of the tides that have happened before ..." (3.28.6).

The description is certainly inspired by information about giant tidal waves caused by earthquakes. But does the sea have its sources in the form of underground 'veins', about which Seneca (and before him Plato and some other philosophers) speaks? According to Aristotle, unlike rivers or springs, the sea does not 'flow out of somewhere' (Aristotle, *Meteorology* 353b17 ff.),[10] but even in the seas there are localized currents, like those that cause the tides, and more permanent ones, just as the Maeotis flows into the Pontus and the Pontus into the Aegean (354a1 ff.). Tidal currents are especially felt in narrow straits, where small fluctuations in sea-level must seem great, whereas they are scarcely perceptible on the expanse of sea.[11]

Currents, as Aristotle notes elsewhere, also exist underground, not only of water but also of exhalation (*pneuma*). Thus, trying to explain earthquakes by the underground movement of exhalations, he states that they are more likely to occur in calm weather, since 'the exhalation being continuous in general follows its initial impulse tends either all to flow inwards at once or all outwards' (366a7). It follows that earthquakes often occur at midday and at night, because at that time all winds usually weak, or at any time of day when different winds compensate for each other. During

[10] On the contrary, the aforementioned Peripatetic Strato believed that currents are related to the rise and fall of the seabed, that is, as Strabo says, "thought that the phenomena occurring in rivers also take place in the sea" and that "the sea current originates from high places, otherwise he would not have considered the seabed as the cause of the currents at Byzantium" (*Geography* 1.3.5).

[11] In the treatise *On Things Heard* 55 (834b3) of the *Aristotelian corpus*, for example, it is said that the water level in the strait between Sicily and Italy fluctuates depending on the phase of the moon. Herodotus (*Hist.* 7.198) notes that Xerxes marched along the Malian gulf where "all day long there are tides".

the day the exhalations rise up and move outward, like the tide, and at night they rush inward again, like the tide. This is why earthquakes are especially frequent towards dawn, for it is at this time that the morning breeze usually rises: “If the original impulse of the exhalation changes direction, like Euripus, and turns inwards, it causes a more violent earthquake because of its quantity” (*Meteorology* 366a10 ff.).

In addition, Aristotle continues, strong earthquakes occur in places where there are swift sea currents and the soil is porous and riddled with caves, through which sea water can go underground, and the heat of the earth, on the contrary, go outside. As examples, among other places, he mentions Aedipsos (modern Loutra Edipsou), a place on Euboea (modern Evia), abundant in thermal springs, located in the North Evian Gulf, into which the Euripus Strait leads (see Fig. 1.). Does this mean that Aristotle believed that the reason for the change of direction of the current in Euripus was the periodic filling of the underground caves in Aedipsus with water? As we have seen, such an explanation is found in ancient natural philosophers, which is confirmed by Seneca (NQ 3.16.1, quoted above).

The phenomenon of flow in the straits, and especially the reverse flow, intrigued ancient authors. Strabo (*Geography* 1.3.11–12), referring to Eratosthenes, says that any currents in the sea arise, as in rivers, because of the difference in water level, but their character can be very different and such phenomena as the Sicilian Strait, which changes the direction of its current twice a day, or Chalcis, which change it seven times a day, are phenomena that require more in-depth study. The tide as a direct cause of this phenomenon is not mentioned here, although such an explanation was already available, as we have just seen, to Aristotle, while Seneca[12] attributes to Herodotus a strange view that the Nile is spreading because the sun, “crossing the southern belt close to the ground, attracts the waters of all the rivers to itself ”and therefore, when it begins to lean to the north, it draws the waters of the Nile behind itself. Here he also refers to Dicaearchus, a pupil of Aristotle, who thought that the Nile overflowed (ἀναχεῖσθαι)

[12] QN 4.1 is not preserved, but quoted by John Lydus.

from the Atlantic side, [13] and suggested the following mechanism for the origin of the tides. In his opinion, the seas are overflowed (πλημμύροντι) precisely under the influence of the sun, which "every time carries them (ἀποσυυυ) from the places from which it retreats, and these deviations (ἐκκλίσιες) occur in the morning and immediately after noon" (Stobaeus, *Anthology* 1.38.2; fr. 127 Mirhady). Aristotle in *Meteorology* (366a13 ff.) speaks of a "deviation" due to a change in the direction of the wind. Dicaearchus probably also associates tidal phenomena with night and day breezes.

Tides attracted Posidonius, who according to the doxographer (Aetius, *Placita* 3.17.4 = Stobaeus, *Eclogae* 1.38.4; 1.253.1; fr. 138 Kidd), wrote that "the winds are driven by the Moon; winds set the sea in motion, where this phenomenon occurs (i.e., tides)." This testimony is not very clear. According to Priscian (*Answers to Chosroes* 6.72–73 = Posidonius, fr. 219) the Stoic philosopher developed another physical analogy. Since the sun and the moon spread heat, which can heat the water, and the heat from the sun is strong and dry (it is pure fire), and from the moon is weak and moist (since the fire in it is mixed with air, Posidonius, fr. 122) it is natural to assume that the heat from the sun simply evaporates moisture, while the heat distributed by the moon creates turbulence on the surface of the water, similar to that which occurs in a pot heated over low heat. Pliny repeats the same idea (*Natural History* 2.222–223). The analogy must go back to Aristotle, who, incidentally, rejects it, along with the theory that the celestial bodies "fed by moisture" (*Meteorology* 355a25). Similar speculations are found in Epicurus, who in the *Letter to Pythocles* (Diogenes Laertius 10.110), in the context of discussing the nature of the halo around the moon, notes that it can occur either because the air rushes to the Moon (as a

[13] Cf. John Lydus, *On the Months* 4.107. The opinion that the Nile flows from the Atlantic was expressed by one of the earliest explorers of African continent Euthymenes of Massalia (NQ 4.2.22), who linked the rise of the water in the Nile with the summer northern winds (the Etesian winds), which usually begin in early July with the rising of Sirius. In addition, on the Atlantic coast of Africa, he saw the river (most likely, Senegal), in which the crocodiles lived, and concluded that they swim in the Nile. Most likely, Dicaearchus shares the opinion of this geographer.

celestial body) from all sides, or because that, encountering resistance, the air is concentrated around it by a uniform ring, or because all the outflows from the Moon itself are restrained by this ring. That is, in the first case, repulsive forces act, and in the second and third – the forces of attraction.[14] Of course, this is all rather speculative, but it is unlikely that a better physical explanation of such a complex phenomenon as the tide was possible before Newton's discovery of the theory of gravitation and Laplace's construction of the dynamical theory of tides.[15]

The observed phenomenon itself was explained more or less correctly by ancient authors, who definitely associated tidal waves with the phase of the moon and, in part, with the location of the sun and were able to give them a relatively reliable explanation. According to Strabo, Posidonius studied these phenomena most carefully, and constructed his theory on the basis of personal observations (*Geography* 1.1.9, 1.3.12, etc., Posidonius, fr. 214–229). In particular, interpreting Homer,[16] Posidonius tried to explain ocean currents by tidal phenomena, against which Strabo (1.1.7, with a reference to Crates) reasonably objects that a tidal wave, moving to the shore, is quite different from a regular current, even if it changes its direction. Therefore, when Homer speaks of the Ocean as 'flowing backwards' (*Odyssey* 20.65), he most likely means a surge in a bay or a lagoon.

The astronomical description of the tides in Posidonius is also connected with the theory of underground waters driven by *pneuma* – in the spirit of the same ancient analogy between the structure of the subterranean realm and the living organism. Strabo reports that in the temple of Hercules in

[14] The texts: Long, Sedley 1987. On cosmological background of Epicurus' meteorology, cf. Eliopoulos 2015 and, esp., Bakker 2016.

[15] For a general discussion of this complex natural phenomenon, see, for example, the following, both popular and more specialized books: Cartwright 1999 and Souchay, Mathis, Tokieda 2013 (ch. 2), McCully 2006.

[16] Homer's assertion (*Odyssey* 12.105) that 'three times a day' the ocean "belches forth" and "sucks down" water Posidonius explains by a distortion of the text. After all, it is known that the tide comes twice a day (and so does the strait of Sicily).

Gades (now Cadiz), according to Polybius (*History* 24.9.5), who visited those places, there is a spring which, strangely,

> "... subsiding at the flow of the tide, and springing at the ebb. He assigns as the cause of this phenomenon, that air rises from the interior to the surface of the earth; when this surface is covered by the waves, at the rising of the sea, the air is deprived of its ordinary vents, and returns to the interior, stopping up the passages of the spring, and causing a want of water, but when the surface is again laid bare, the air having a direct exit liberates the channels which feed the spring, so that it gushes freely" (*Geography* 3.5.7, tr. H. C. Hamilton, W. Falconer).

Posidonius, who spent much time in Gades during his sea voyage, takes the story about the spring to be false, and observes that in reality the wells at Heracleon and another in the city run dry simply because people draw water from them during the day and they fill up again at night. And since the time of low tide often coincides with the time of filling the source, the residents of Gades mistakenly link these events as if one were the cause of the other (ibid.). Strabo is inclined to accept the explanation of Polybius and, relying on another biological analogy of the disciple of Posidonius Athenodorus, according to which the tides are the inspiration and expiration of the "breath" of the sea, suggests that

> "...it is possible that some of the currents of water which naturally have an efflux on to the surface of the earth, through various channels, the mouths of which we denominate springs and fountains, are by other channels drawn towards the depths of the sea, and raise it, so as to produce a flood-tide; when the expiration is sufficient, they leave off the course in which they are then flowing, and again revert to their former direction, when that again takes a change" (ibid.).

We have already met this explanation in Aristotle. Apparently, Posidonius does not agree with him, and, as Strabo further testifies, develops an astronomical explanation of tides, complementing theoretical considerations with personal observations. Periodic movements of the ocean repeat, he says, the periods of revolution of celestial bodies, and we can distinguish daily, monthly and annual periods:

> "... when the moon is elevated one sign of the zodiac [30 grades] above the horizon, the sea begins sensibly to swell and cover the shores, until she has attained her meridian; but when that satellite begins to decline, the sea again retires by degrees, until the moon wants merely one sign of the zodiac from setting; it then remains stationary until the moon has set, and also descended one sign of the zodiac below the horizon, when it again rises until she has attained her meridian below the earth; it then retires again until the moon is within one sign of the zodiac of her rising above the horizon, when it remains stationary until the moon has risen one sign of the zodiac above the earth, and then begins to rise as before" (*Geography* 3.5.8).

This is the diurnal revolution, corresponding to the phenomena, observable in this region. It needs not to be universally valid.[17] According to Posidonius, Seleucus of Babylon (the 2nd c. BCE) noticed the peculiarities of the diurnal tidal circles in the Persian Gulf:

> "...the regularity and irregularity of the ebb and flow of the sea follow the different positions of the moon in the zodiac; that when she is in the equinoctial signs the tides are regular, but that when she is in the signs next the tropics, the tides are irregular both in their height and force; and that for the remaining signs the irregularity is greater or less, according as they are more or less removed from the signs before mentioned" (3.5.9).

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[17] См. Souchay, Mathis, Tokieda 2013, 104 fig. 3.5 (the authors: B. Simon et al.). The tide map published here shows well that in the area of Cadiz the semi-diurnal tides dominate (two maxima and two minima per day). By the way, most of the Mediterranean Sea is in an area where the semi-diurnal tide is markedly complemented by a diurnal tide (one maximum and one minimum per day), with diurnal tidal peaks being particularly noticeable in the western Mediterranean (the southern coast of Spain and the opposite African coast, especially in the Balearic Islands) and in the south-western Aegean (in the Cyclades). Tide charts in any region of the world can also be viewed on the World Tides service page (https://www.worldtides.info).

This observation corresponds to a ‘mixed type’ of tide, characterized by overlapping diurnal and semi-diurnal cycles.[18]

Posidonius goes on to offer an astronomical theory of the tides, noting that during the lunar month the tide clearly depends on the phase of the moon: it reaches a maximum at new moon (αἱ συνόδαι) and full moon (πανσέληνος), and a minimum at first and third quarter (διχοτόμος and διχοτός φθινάς), which is again true. Finally, referring to the observations of the inhabitants of Gades, Posidonius accepts the annual period,[19] but, as Strabo further reports (3.5.9), although our philosopher spent many days in Gades during the summer solstice, which then occurred around the new moon, he was never able to record the phenomenon:

> “Posidonius adds, that during the summer solstice and whilst the moon was full, he himself passed many days in the temple of Hercules at Gades, but could not observe anything of these annual irregularities. However, about the new moon of the same month he observed at Ilipa [Alcolea] a great change in the reflux of the water of the Guadalquiver, as compared with previous flood-tides, in which the water did not rise half as high as the banks, and that then the water poured in so copiously, that the soldiers

[18] Cf. Souchay, Mathis, Tokieda 2013, 104 fig. 3.5. The map shows that such a tide is indeed observed in some regions of the Indian Ocean, in the central part of the Red Sea and in the Gulf of Aden.

[19] According to Strabo, a one-year maximum should occur during the solstice and a minimum during the equinox. This is an obvious mistake, thanks to the independent testimony of Neo-Platonist Priscian, who reports that in fact, Posidonius assumed that the tides reach a year’s maximum during the equinox: during the full moon and the new moon (*Answers to Chosroes* 6.71 and 73 = Posidonius, fr. 219). By the way, there is a longer tidal cycle: every few centuries the location of the Moon, the Earth and the Sun relative to each other is repeated, which causes long tidal cycles: approx. 300 BCE the tides were about the same as now, around 550 CE they reached a relative minimum, in 1400 they were again the maximum, and the next minimum is expected in about 2400 (Carter 1966, 11).

there dipped their supply without difficulty, although Ilipa is about 700 stadia from the sea." [20]

Similar information is given by Pliny (*Natural History* 2.212 ff.), Flavius Philostratus (*The Life of Apollonius of Tyane* 5.6) and other ancient authors. Priscian also mentions this phenomenon, adding to Posidonius' list the Rhine and the Thames, which, according to his information, can even reverse their current during the high tide. We call this phenomenon boron.[21] Strabo (again with reference to Posidonius) mentions the phenomenon on the Iber River (modern Ebro). According to Posidonius, boron happens on the river due to the fact that the north wind from the lake through which the river flows, drives the waves into the river. In addition, the tidal wave was quite able to cause a positive set-up of water at the mouth of the Ebro, since at the time of Posidonius the river did not yet have a vast delta, as is observed now. Commentators note that, to our knowledge, Posidonius himself did not visit these places, so this remark of Strabo is not very clear. However, if we remember that it is in the Ebro area that the Spanish coast is subject to anomalous diurnal tides (the only region in the western Mediterranean), it becomes clear why this report is

[20] For readers convenience, I will quote the rest this interesting and rare description: "He says, that the plains next the sea were covered by the tides to a distance of 30 stadia, and to such a depth as to form islands, while the basement of the temple in the enclosure dedicated to Hercules, and the top of the mole in front of the harbour of Gades, were not covered higher than 10 cubits, as observed by actual soundings; but if anyone should add the double of that for the occasional risings of the tide which occur, [neither] thus would he be able to estimate the violence with which the full force of the high tide rushes over the plains. Posidonius informs us that this violence [of the tide] is common to all the coasts of Spain on the Atlantic, but what he relates concerning the Ebro is unusual and peculiar to itself, for he says that it sometimes overflows after continued north winds, although there may have been neither rains nor snows. The cause of this [he supposes] to be the lake through which the Ebro flows, its waters being driven by the winds into the current of the river."

[21] The most well-known examples are: boron in the mouth of the Fuchunjiang, Amazon, Ganga and other large rivers with a wide and funnel mouth; less significant boron is observed in European rivers (Severn, Trent, etc.); note also unique "reversible waterfalls" on the St. John's River, which flows into the Bay of Fundy.

given in addition to Seleucus' observation of similar tides in the Indian Ocean (completely atypical for the Atlantic and Mediterranean).

Why does the current in the Strait of Chalcis (Euripus) change its direction? It is clear that Strabo was closest to the truth, but the final answer to this question was received only in our time. The full and accurate description was first introduced by the Greek astronomer D. Eginitis (1929). The root cause of this amazing phenomenon is indeed the tides, but its exact description is impossible without taking into account a number of local features, as well as the strength and direction of wind and waves.

At present, Euripus is a narrow and short canal (39 m wide and 40 m long) that separates the island of Euboea (modern Evia) from mainland Greece. This relatively deep (8.5 m) passage is used for shipping: the bridge connecting the coast moves apart once a day and passes through various sea transport (see Figure 3).

The phenomenon, as already mentioned, is as follows: (1) periodically the flow in the strait changes very quickly to the opposite, usually every six hours, but on some days these changes become erratic (at squaring phases of the tide); (2) the speed varies during the lunar month, sometimes it is relatively weak, sometimes reaches six or even nine nautical miles per hour, which makes it difficult to pass through the canal, especially for small vessels.

Based on the almanac issued by the port service of Chalkida, it is possible to make approximately the following table of the flow direction change in the strait depending on the phase of the moon (for a given synodical month). The table shows the typical timing of flow changes.[22] N – S means flow from north to south, and S – N from south to north.

New Moon	N–S	S–N	N–S	S–N
1	03.15	09.30	15.50	22.05
2	03.45	10.05	16.20	22.30

[22] For a clear description of the phenomenon, see the article by Antonios Antoniou (2015), an astrophysicist of the University of Athens.

3	04.10	10.30	16.40	22.50
...	...	...	...	...
6	06.00	12.00	18.10	–
7-9		Irregular	stream	
10	00.00	06.10	12.10	18.10
11	00.30	06.40	12.50	18.10
...	...	...	...	...
20	05.40	11.50	17.55	00.10
21–23		Irregular	stream	
24	00.00	06.10	12.10	18.20
25	00.30	06.40	12.50	18.50
...	...	...	...	...
28	02.10	08.25	14.30	20.40
29	02.45	08.55	15.10	21.05

Within 24 hours and 50 minutes we observe four phases of flow change, which corresponds to the interval between two successive passes of the meridian by the moon. It is clearly seen that the periods of regular change in the direction of flow alternate with two periods of relative disorder, when the flow can change direction up to 14 times a day, which corresponds to, as the table clearly shows, the time the moon is found in the first and last quarter.

It is clear that the strongest and most regularly changing currents are observed during the spring (sisygian) tide, when the gravitational forces of the Moon and the Sun, which are in line with the Earth, mutually reinforce each other, while weak and irregular currents occur during the neap (squaring) tide, when the forces of the Sun and the Moon act at right angles to each other. Small (about a foot) Mediterranean tides, which can be amplified or weakened by surge events in the northern and southern gulfs of Evia, caused by strong southerly and northerly winds, respectively, should theoretically be sufficient for a current to form in the strait.

Let us look at the map of Evia (Fig. 1). This huge and mountainous island extends one hundred and ten miles from the southeast to the northwest. The vast Southern Gulf of Evia opens from the south-west like a large horn, from which the Cyclades are like pouring out, while the North Gulf of Evia is connected with the Aegean Sea by a narrow and relatively shallow channel, the entrance to which is closed by a group of islands (Skiathos, Skopelos, Alonissos and others). Let us now consider how the tidal wave will travel, moving across the Mediterranean from east to west. Obviously, it will reach the Southern Gulf earlier than the Northern one. As the observations show, the time difference will be 1 hour and 15 minutes. The wave that entered the South Gulf of Evia provides a rise in water level of about one foot and creates a current from south to north in the Euripus Strait. Approximately six hours later, a narrow strait reaches the oncoming wave from the Northern Gulf of Evia and the flow first stops and then its direction changes to the opposite. The exact time of passage is determined empirically and depends on a number of factors, such as the difference in depth in the bays, the outline of the coast (the North Bay connects with the sea by a narrow channel and, passing through it, the tidal wave encounters many more obstacles on its way than in the open South Bay), wind direction, etc.

Of course, ancient astronomers did not understand the physical nature of tidal phenomena, but they were quite capable of making empirical observations, accumulate them, and (to some extend) conduct experiments. The problem, as we see, is that even accurate knowledge of tidal forces alone does not explain the change of current in the strait, which must have given rise to alternative theories about the regular surfacing of underground water in the Gulf of Aedipsus.

Illustrations

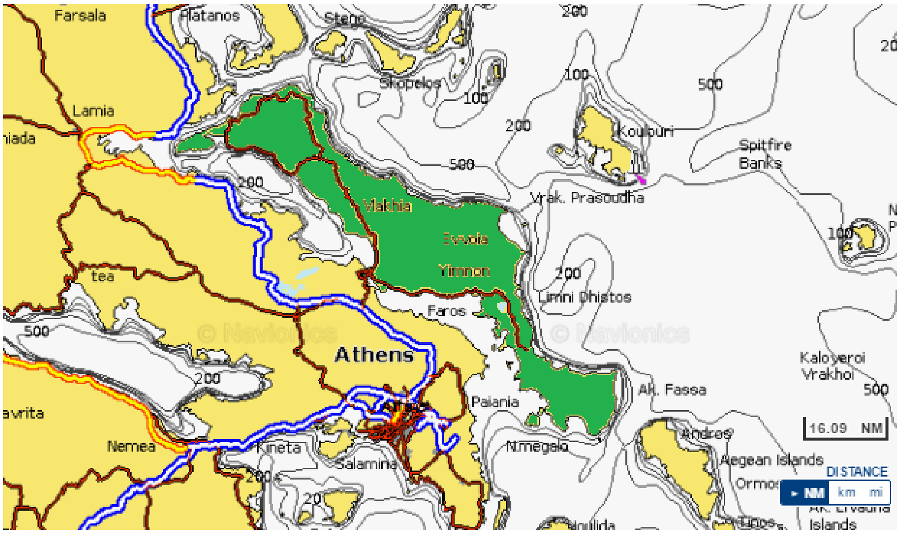

Fig. 1. Evia (marked in green). A fragment of a naval map.

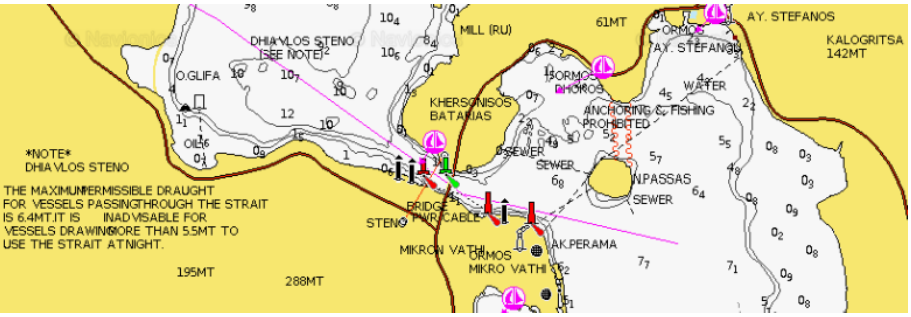

Fig. 2. Euripus. A fragment of a naval map.

Fig. 3. Euripus. A general view.

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