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COPIA AQUARUM: FRONTINUS' MEASUREMENTS AND THE PERSPECTIVE OF CAPACITY

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Metropolitan Rome, that *domina orbis*, could point with special pride to one of the gems in her imperial crown: a copious, ever-flowing supply of public water. The aqueducts of Rome were a wonder to the world. How much water did they bring to the City? The question recurs, posed most obviously by those who seek to understand the Romans' mastery of engineering skills, but posed as well by historians for whom the answer can provide an interesting glimpse at the reality of urban life and standards. We happen to have the answer—or an answer, or part of an answer. Frontinus, *curator aquarum* appointed by Nerva in A.D. 97, included precise figures for the *copia aquarum* in a personal notebook which he compiled soon after he took office (subsequently revised and expanded for publication as a kind of political statement of the Trajanic ideal of senatorial administration). Aqueduct by aqueduct, he tells us the quantity (*modus*) of water, both the supply available (*conceptio*) and the amount delivered (*erogatio*). His data came directly from the imperial records, but he went beyond these "authoritative" figures, taking measurements of his own and subjecting the records to an exhaustive and critical review. Translate the information Frontinus gives us into modern terms, and we shall know how much water flowed into Rome at the end of the first century.

Conversion comes by no means readily. We express quantity in units of volume and time (litres per second, for example); Frontinus had a single unit (the *quinaria*), which expresses neither volume nor time but only the capacity of the pipe or conduit. "Capacity" means the cross-section of flowing water: in the case of closed pipes this is the area of the opening (also called its *lumen*). A *quinaria*, then, is the capacity of a "number-five pipe" (the *fistula quinaria*, defined by its diameter of five quarter-digits, approximately 23 mm).[1] An expression of capacity

[1] Frontinus 25.4 (*quinariam dictam a diametro quinque quadrantum*) and 26.2 (*utendum est substantia quinariae*). Frontinus' *De Aquaeductu Urbis Romae* is available in the Teubner text of C. Kunderewicz (Leipzig 1973), the Loeb of C. E. Bennett (1925), and the Budé of P. Grimal (1944). I am currently preparing a critical edition and commentary.

totally neglects both volume and time; to speak of quantity in terms of capacity is fundamentally alien to the modern viewpoint. The ancients, of course, could measure volume, and commercial standards existed for commodities like wine and oil. They could also, albeit less exactly, measure time. They had no convenient method of measuring both volume and time—in other words, velocity (although the notion of velocity and its general effect did not escape them).[2] But let us not lose sight of our immediate problem: how they measured public water flowing constantly. Time in this case had no special relevance,[3] and volume (which could have been expressed, if one had wished, in *congii* or *amphorae*) was essentially unimportant. This is not to say that quantity itself was of no concern, but in practice quantity was seen to be limited only by the capacity of the vehicle which conveyed it. Thus we can understand why Frontinus was content to express the quantity of public water in terms of capacity.

Frontinus' unit, the *quinaria*, was the standard measure in use at Rome. It is important to recognize that Frontinus did not himself devise this standard or define the circumstances under which it could be applicable. Like the standardized nomenclature for pipes (to which it is plainly related), we can safely suppose that measurement in *quinariae* was introduced as part of the large-scale reorganization of Rome's water system carried out more than a century earlier by M. Agrippa. The creation of a city-wide standard for deliveries would have been eminently practical in regularizing grants to private consumers, a practice greatly expanded under Agrippa. Applied on a larger scale, it would aid in his coherent plan for efficiency of distributing water for various uses and to all parts of the City.[4]

How could a unit based on capacity be treated as a standard? Pipes of exactly equal size will not necessarily deliver the same amount of water, for hydraulic factors other than cross-section are at work. We know that quantity is the product of velocity and area; we also know that velocity in closed pipes relates to the head, adjusted by the loss to resistance. Frontinus knew much the same thing. He speaks of

[2] A point made clearly (for the first time, so far as I know) by A. Trevor Hodge, "How Did Frontinus Measure the Quinaria?" *AJA* 88 (1984) 205–6.

[3] In circumstances where the flow was not expected to be constant, time could be used as a means of division. Frontinus describes such a procedure for the Crabra near Frascati (9.5): "All the villas in that region receive this water by turns, partitioned by fixed days and pipes." There is epigraphical evidence for similar arrangements elsewhere (e.g. *CIL* VI 1261 and 31566).

[4] Frontinus 98.2: "Now that the supply permitted, Agrippa determined the proportion of water to be allotted to public buildings, to public fountains, to private consumers." An excellent survey of the long series of Agrippan accomplishments is that by Harry B. Evans, "Agrippa's Water Plan," *AJA* 86 (1982) 401–11.

head (*pressura*) and of resistance (*segnitia ductus*), and—tantalizingly—he mentions that there are ways of compensating for inequalities they produce.[5] To establish a uniform head was an obvious solution, one which could have been easily effected in delivery tanks: all discharge pipes were to be set at the same level within a tank, and some tanks at least had an overflow.[6] If we knew what this head was, we could calculate the standard *quinaria* according to the formula $Q = A\sqrt{2gh}$. But we do not know—either from Frontinus, for whom details such as these were largely irrelevant, or from any surviving archaeological remains.[7] We can make reasonable guesses, but the only certainty, it seems to me, is that the *quinaria* (an expression of capacity) was a workable unit for quantity because velocity had been standardized.[8] That its original application was for urban deliveries is virtually certain, and within the hydraulic context of closed-pipe distribution the term had a meaning which entirely satisfied the Roman viewpoint. Frontinus, therefore, would have had no difficulty in understanding or interpreting the figure of 14,018 *quinariae* which his records showed for the total urban delivery.

[5] Frontinus 35: "We remember that water coming from a higher place and falling into a tank within a short distance will not only deliver the quantity according to pipe-size but will surpass it. Coming, on the other hand, from a lower place (that is, with less pressure) and carried a greater distance, it will lose in quantity because of the slowness of the channel. Accordingly, water must be 'burdened' or 'relieved' in respect to delivery." ("Memineramus omnem aquam, quotiens ex altiore loco venit et intra breve spatium in castellum cadit, non tantum respondere modulo suo sed etiam exuberare; quotiens vero ex humiliore, id est minore pressura, longius ducitur, segnitia ductus modum quoque deperdere; et ideo secundum hanc rationem aut onerandam esse erogatione aut relevandam.")

[6] Frontinus 113.1: "In positioning the delivery-nozzles it is important to observe that they be arranged on an even level so that one person's nozzle is not set lower while another's is higher." ("Circa conlocandos quoque calices observari oportet ut ad lineam ordinentur nec alterius inferior calix alterius superior ponatur.") For overflows note 111.2: "It is necessary that some water escape by overflow from the tanks" ("necesse est ex castellis aliquam partem aquae effluere")—although in context the purpose is to scour the drains; cf. 110.1 (on *aquae caducae*): *quae aut ex castellis aut ex manationibus fistularum effluunt*. An overflow would establish uniform head, of course, only so long as water continuously overflowed.

[7] Although details at Rome will no doubt have been very different, it might be profitable to consider the distributory system well preserved at Pompeii: see H. Eschebach, "Die innerstädtische Gebrauchswasserversorgung dargestellt am Beispiel Pompejis," *Journées d'Etudes sur les aqueducs romains*, Lyon May 1977 (Paris 1983) 81–132; J. D. Larsen, "The Water Towers in Pompeii," *Analecta Romana Instituti Danici* 11 (1982) 41–67.

[8] At least within a range that could be called "normal," judged by reasonably even discharge in all parts of the City. Universally accepted as a minimum value for the *quinaria* in a closed-pipe system is the figure of 0.48 litres/second (based on a minimum head of 12 cm) formulated by C. DiFenizio, "Sulla portata degli acquedotti romani e determinazione della quinaria," *Giornale del Genio Civile* 14 (1916) 227–331. DiFenizio's figure, oft cited, was for what he felt to be a *minimum*. One should not forget that we have *no evidence* for any standard save that for capacity. Fixing the head strikes us as easy and obvious, but our ignorance is probably too vast to warrant such confidence.

From the same records, however, another figure leapt to Frontinus' eyes: the total available supply came to 12,755 *quinariae*. Was it not astonishing that delivery exceeded supply? Personal scrutiny was plainly called for, and Frontinus spares no effort in sharing with his readers every stage of his investigation. We may confidently assume that he knew what a *quinaria* was, but he seems to have had no idea as to the origin of the official figures for supply. The records referred to *concepta* or *conceptio*, which Frontinus apparently took to mean "at the source" (*ubi aqua concipitur*). The obvious starting-point was for him to take measurements at the source.[9] Another set of measurements could easily be taken at the settling-tanks (*piscinae*) just outside the City.[10]

Just how did Frontinus take his measurements? He explains his procedure in some detail as he reports the first one (that for Aqua Appia): "I found the water had a depth of 5 feet, a width of 1¾ feet. This gives an area of 8¾ square feet, which is the equivalent of 22 centenaria pipes [i.e. 22 × 100 square digits] plus one quadragenaria pipe [40 square digits]. This is the equivalent of 1825 *quinariae*."[11] This measurement, for all that we can tell, is based on the cross-section of water flowing freely in the aqueduct channel. In the case of Marcia, he measures 4690 *quinariae* at the source, and then he remarks that there was in addition an overflow of more than 300 *quinariae* "besides that measurement which we had calculated from the capacity of the conduit."[12] Reckoning by capacity is implicit as well in a comment on Claudia: "whose channel does not accommodate all the water."[13]

Frontinus' measurements revealed that the total available supply was 24,413 *quinariae*, "practically double" the figure he had found in the records and "some 10,000 *quinariae*" above what the records showed for delivery.[14] It was good to be assured that supply indeed exceeded delivery (as anyone would have expected). But the comfort he derived from this demonstration had then to be tempered by astonishment at the discrepancy between his measurements and the official figures. The records, he guesses, were in error because those figures for supply had been reached by inaccurate or inadequate methods: "The explanation is

[9] Frontinus 64.4: "My first task was to measure the intakes of the conduits." ("Ante omnia igitur capita ductuum metiri adgressus sum.")

[10] Frontinus 19.2: "The quantity of water is also calculated by gauges set up here." ("Modus quoque earum mensuris ibidem positis initur.")

[11] Frontinus 65.3: "Inveni altitudinem aquae pedum quinque, latitudinem pedis unius dodrantis: fiunt areae pedes octo dodrans, centenariae viginti duae et quadragenaria, quae efficiunt quinarias mille octingentas viginti quinque."

[12] Frontinus 67.9: "Praeter eam mensuram quam comprehendisse nos capacitate ductus posuimus."

[13] Frontinus 72.8: "quamvis ne huius quidem ductus omnem aquam recipiat."

[14] Frontinus 87.3: "prope duplicata ubertas est," and 64.4: "longe, id est circiter quinariis decem milibus ampliorem quam in commentariis modum inveni."

error on the part of those who initially made the calculations for each aqueduct; their performance was something less than competent."[15] Records for official deliveries were taken to be correct, yet he had somehow to account for the 10,000 *quinariae* available but not officially delivered. A ready explanation was to hand: he had everywhere detected flagrant cases of fraud and theft.[16]

What kind of confidence did Frontinus place in his measurements? In the case of Anio Vetus (where he measures both at the source and at the settling-tank) he calculates losses at 2788 *quinariae*, so large as to be initially embarrassing: "I would have suspected an error in measurement had I not detected where these amounts were being diverted."[17] Even more revealing is his confession in discussing the Anio Novus. Measured at the source were 4738 *quinariae*; records for delivery showed 4200. But his investigation had uncovered losses well in excess of the apparent difference of 538 *quinariae*. "It is clear that the supply exceeds the measure we established: the reason is that the water is taken from a swift-flowing river and its velocity increases the available quantity."[18]

How reliable are Frontinus' measurements from a hydraulic standpoint? We now understand—as perhaps he did not—that hydraulic conditions in open flow differ quite markedly from those in a closed-pipe system.[19] While the *quinaria* (a unit of capacity) could be exact and meaningful in the case of submerged pipes, it is a serious error to apply the same standard of capacity to water flowing freely in aqueduct channels. Quantity is still the product of velocity and area, but here velocity is determined by the gradient and cannot readily be adjusted to a uni-

[15] Frontinus 74.2: "cuius rei causa est error eorum qui ab initio parum diligenter uniuscuiusque fecerunt aestimationem." *Facere aestimationem* pointedly contrasts with Frontinus' own *mensurae*. He dismisses the earlier figures as mere approximations, less reliable than his own measurements.

[16] A point accurately and emphatically made by C. Herschel, *The Two Books on the Water Supply of Rome* (Boston 1899; 1913²) 203. That his explanation might lack hydraulic validity would not have occurred to Frontinus. His reports on quantities diverted are in general too vague to give us an idea of how precisely he may have reconciled all his data: but it was hardly his aim to catalogue *illicita*!

[17] Frontinus 66.7: "Quod errore mensurae fieri suspicarer, nisi invenissem ubi averterentur."

[18] Frontinus 73.6: "Ex quo adparet etiam exuberare comprehensam a nobis mensuram: cuius rei ratio est quod vis aquae rapacior, ut ex largo et celeri flumine excepta, velocitate ipsa ampliat modum."

[19] D. R. Blackman, "The Volume of Water Delivered by the Four Great Aqueducts of Rome," *PBSR* 46 (1978) 52–72. Blackman's approach is independent of Frontinus and DiFenizio, but his results are, as he puts it, in "modest agreement" with DiFenizio's calculation for a minimum value for the *quinaria*. "Modest agreement" overall does not establish certainty, and Blackman is at pains to point out that the aqueduct channels in some cases cannot have carried a volume of water which corresponds to Frontinus' figure converted by DiFenizio's calculation for the *quinaria* minimum.

form standard. So far as we can tell, however, Frontinus' measurements (in *quinariae*) are expressions of capacity,[20] and it follows that his supposition was scientifically invalid. Was he aware of this difficulty? In part he was, for he recognizes that velocity can affect a calculation based on capacity. We have already noted his comment on the unusual velocity at the intake of Anio Novus which distorts his reckoning. For some aqueducts he takes no measurements at the source, explaining that the system of collecting feeders makes this impossible. With Virgo he is more explicit: "A measurement cannot be taken at the source because there are several catchment channels and water enters the conduit too slowly." At a later point he can measure, "where the water has a swifter flow."[21] By disregarding extremes of velocity, Frontinus is dealing, as it were, with "normal" or relatively uniform flow, such as that when water from a catchment-tank enters the conduit or when it leaves the settling-tank. To equate "normal flow" in the main aqueducts with "normal flow" in closed pipes is not so unreasonable if we remember to keep ourselves within the ancient perspective where capacity is the measure of quantity. The equation is wholly invalid, of course, in modern terms. Frontinus' careful measurements are totally useless for our purposes: they simply cannot be translated into expressions of volume and time. We had counted on Frontinus as a knowledgeable witness. To conclude that he has failed us is a severe disappointment.

We could restore our trust in Frontinus by demonstrating that the *quinaria* of his measurements is indeed the exact equivalent of the *quinaria* standard in urban deliveries. Various scholars have made the laudable attempt to show how Frontinus' procedure is not really at odds with our superior understanding of hydraulic science. The most convincing suggestion is that recently discussed by A. Trevor Hodge.[22] Frontinus' measurements, he argues, are not those embarrassing measurements of simple cross-section. By lowering a sluice into the water flowing in an open stream, one can artificially create the same conditions which obtain in submerged pipes. When the head behind the sluice equals that accepted as standard in delivery tanks, the cross-section of

[20] The measurements at the sources of the four main aqueducts convert to the following: Anio Vetus, 4398 *quin.* = 1.85 m^2; Marcia, 4690 *quin.* = 1.97 m^2; Claudia, 4607 *quin.* = 1.94 m^2; Anio Novus, 4738 *quin.* = 1.99 m^2. These figures closely approximate the sizes of the channels; it would not be unreasonable to imagine that they "ran full" at the point where water entered from catchment-basins. Blackman (see preceding note) concludes that the discharge of these four aqueducts was around 7 m^3/second (600,000 m^3/day).

[21] Frontinus 70.2–3: "Huius mensura ad caput inveniri non potuit quoniam ex pluribus adquisitionibus constat et lenior rivum intrat. prope urbem tamen . . . ubi velociorem iam cursum habet, mensuram egi. . . . "

[22] Hodge (above, note 2) 210–14. A special kind of measuring is not Hodge's own proposal: the most authoritative of his predecessors is DiFenizio (cited p. 210, note 19).

water flowing beneath the sluice will be proportionate to that of standardized delivery pipes and thus can accurately be expressed in the same terms.

Unfortunately, Frontinus' text gives no support to such an explanation. Look closely at his methodical statement on measuring Appia (quoted above): there is no mention—here or elsewhere—of any sluice, or any special device for measuring. Without qualification, indeed, his phrase "depth of the water" (*altitudinem aquae*) would be ambiguous in describing a situation where there are in fact two depths (one the water level behind the sluice, the other that of flow beneath the sluice). Nowhere does he give the slightest hint that he is using the verb *metiri* or the noun *mensura* in any other than the obvious sense of reckoning cross-section or capacity.[23] And, on the other hand, he applies the term *capacitas*, surely synonymously, to the channel of an aqueduct and to the cross-section of pipes.[24]

An argument from silence is never strong. Could Frontinus have in fact used a more sophisticated system of measurement but failed to tell us (his intended audience, after all, might have had little interest in technical details)? Such a notion is, I think, wholly unlikely if Frontinus himself (or engineers in his service) were responsible for devising a new system capable of measuring quantity in open flow. To explain the novelty not only would have added weight to his claims of accuracy but also, as an example of administrative *diligentia*, it would have been a useful legacy for his successors.

Frontinus' lack of explanation would make more sense if we could suppose that he inherited a system of measurement. I can find only two arguments to support this view. First, official records had given the supply in *quinariae*. But Frontinus is baffled by these figures, and he sees no way that they might be related to measurements of his own.[25] Second, the "gauges in place" (*mensurae positae*) at the settling-tanks seem to have antedated Frontinus' tenure; it could be argued that they

[23] Frontinus' mathematical logic is beyond doubt: 34.3: "Measurement conforms to exact, inflexible, and self-evident rules." ("Omnia autem quae mensura continentur certa et immobilia congruere sibi debent.")

[24] For aqueduct channels: *Aq.* 67.9 (quoted above, note 12). For pipes: *Aq.* 26.1: "The size of any pipe is determined either by its diameter, its perimeter, or the measure of its cross-section; from these as well its capacity is calculated." ("Omnis autem modulus colligitur aut diametro aut perimetro aut areae mensura; ex quibus et capacitas adparet.") Cf. 36.4: "cross-section, or capacity" ("lumen, id est capacitatem").

[25] By dismissing them abruptly I do not mean to beg the question. The earlier figures for supply are a complete mystery. We cannot know how, when, or by whom they were compiled; nor need we accept Frontinus' charge that they were incompetent guesswork (quoted above, note 15). T. Ashby, *The Aqueducts of Ancient Rome* (Oxford 1935) 30–31 reasonably conjectures that they may have reflected measurements at the settling-tanks (called *conceptacula*: *Aq.* 22.1) or at terminal reservoirs within the City.

were more sophisticated devices from which he learnt the kind of measurement proper for calculating quantity in open flow. I find it on the whole much easier to suppose that these were simple gauges of water depth, and that Frontinus points with such confidence to readings here because they were permanent fixtures by which the skeptical reader could conveniently monitor Frontinus' accuracy.[26] Finally, if Frontinus had inherited his system of measurement, it is extremely difficult to understand why he explains his own methods so carefully—without the slightest hint that he was not giving simple measurements of cross-section in open flow. And it is even harder to understand—if his measuring system was sophisticated enough to be thoroughly reliable—why Frontinus so candidly expresses residual doubts about some of his own measurements.

A brief conclusion. Frontinus' measurements are based on cross-section of water flowing freely in the main aqueducts. He knew what a *quinaria* was in the context of closed pipes within the urban distribution system, but he wrongly assumed that quantity of water in open flow could be reckoned in the same terms. The erroneous assumption arose partly because hydraulic behavior in open channels was less clearly understood, but more specifically because Frontinus' concept of measuring the quantity of public water was defined by the ancient perspective of capacity. In the end, we must after all rely on modern estimates to express in modern terms the answer to how much water Roman aqueducts brought to the capital.[27]

[26] *Positae* (*Aq.* 66.4, 67.5) implies permanent installation; the historical context at *Aq.* 19.2 (above, note 10) suggests that they were in existence prior to Frontinus' administration. He calls them *manifestae* (69.2) and *indubitatae* (72.3).

[27] Professor Hodge and I are cordial in our disagreements, and I gratefully acknowledge his incisive comments on an earlier draft of this paper.