Environment and Population: The Collapse of Large Irrigation Systems Reconsidered

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Irrigation systems were the first source of great abundance that stemmed from the Agricultural Revolution. They were also humanity's first great environmental curse. Long before issues of global warming and freshwater shortages haunted the modern world, irrigation systems blessed and bedeviled humans with their promise and peril. While a well-ordered functional irrigation system provided inhabitants with seed-to-yield ratios that were the envy of any dry-farming regime, these same irrigation systems could collapse in toto, bringing disaster on a scale never seen in rain-fed agricultural systems.

This article will examine the tragic ruin of the irrigation system of Egypt in the wake of Black Death depopulation. It will compare this case to that of the dry-farming system in post-plague England. A comparison between the effects of rural labor shortage in the hydraulic economy of Egypt with labor shortage in the rain-fed economy of England reveals a weakness in the otherwise functional pseudo-Malthusian marginal product of labor function.[1] According to the pseudo-Malthusian model, labor scarcity and land abundance, resulting from depopulation, should lead to higher productivity due to greater marginal returns to labor. Yet, while this did indeed occur in England, Egypt was devastated by labor shortage. Why does this model not seem to work for Egypt's hydraulic system? The answer lies in the second part of the marginal product graph, one that is seldom used by economic scholars of pre-modern history. The following analysis will show that this often overlooked section of the marginal product curve can serve to explain daunting enigmas that lie at the heart of disasters that have affected many irrigation economies.

[1] I use the term "pseudo-Malthusian" here because while the scarcity of land certainly contributed to the loss of life in the 1315–1317 British famine, it probably did not have a significant impact on plague depopulation. (Albeit, William Chester Jordan has suggested that malnourished children from the famine may have been more susceptible victims when struck by the plague as adults. See Jordan 1996:184–85.) A fully Malthusian interpretation of the bubonic plague would hold that it was a direct result of overpopulation and simply a part of a natural Malthusian cycle in pre-industrial history. This theory, in its "extreme," is no longer accepted by historians of England and in any case would do little to explain the "global" scale of the Yersinia pandemic.

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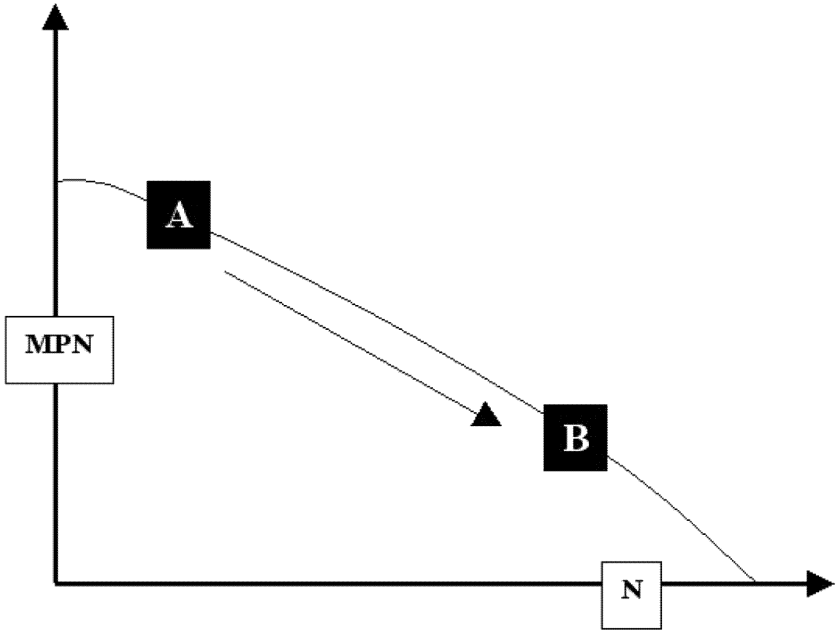


FIGURE 1. Showing the Marginal Product of Labor (MPN) with Increasing Labor on a Fixed Amount of Land

When historians of pre-industrial economies analyze macroeconomic scenarios where population is a key factor, they generally use the concept of marginal returns to show the workings of pseudo-Malthusian logic on its simplest and most transparent level. When land becomes scarce relative to labor (Figure 1), the equilibrium point (points A to B below) moves down and to the right with the average and marginal product of labor, even though the total product of labor may still be increasing (see points A to B on Figure 2). When labor has increased from point A to point B on Figures 1 and 2, the relative overpopulation and scarcity of land will generally be accompanied by rising land rents, falling wages, and decreasing aggregate ("national") output per capita.

If the situation is reversed, and land becomes plentiful relative to labor (Figure 3), the equilibrium point (points C to D on Figure 3) will typically be shown moving up and to the left with the average and marginal product of labor. The relative depopulation and abundance of land will generally be accompanied by falling land rents, rising wages, and increasing aggregate output per capita, even though the total output, "GDP" (agrarian output), may be falling (see points C to D on Figure 4).

That much is typical of rain-fed (dry) farming regions. One of the most famous examples of the pattern seen in figures 1–2 and 3–4 is the contrast be-

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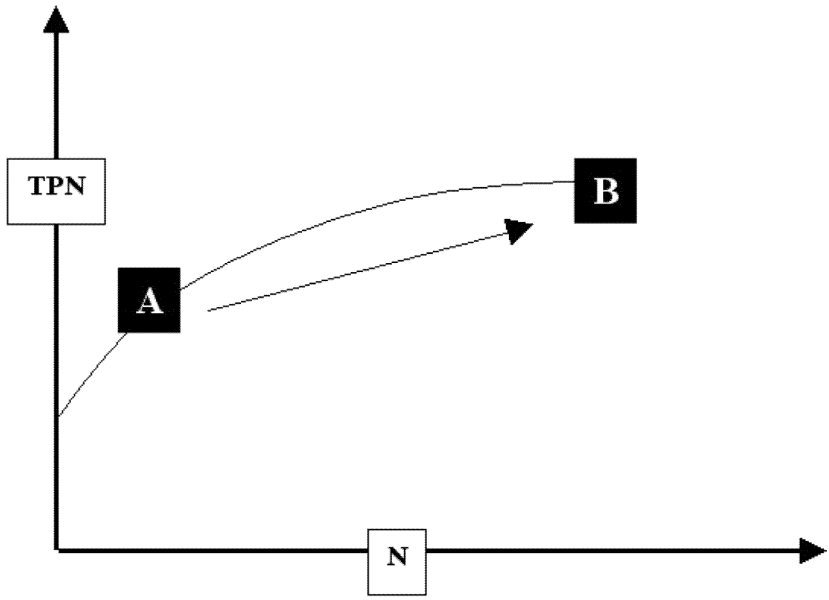


FIGURE 2. Showing the Total Product of Labor (TPN = Agrarian Output) with Increasing Labor on a Fixed Amount of Land

tween England at the end of "long thirteenth century" and England in the fifteenth century (after the Black Death). At the end of the thirteenth century, England's population was quite high relative to land, and land scarcity had brought living standards to a precariously low level.[2] The marginal and total product of labor would have moved from point "A" to point "B," in figures 1 and 2. The disastrous weather that followed in the years 1315–1317 ushered in a horrific famine in which as much as 10 percent of the population is estimated to have died from starvation and malnutrition. By contrast, following mass depopulation from the Black Death and repeated outbreaks of Yersinia pestis, England entered the so-called "golden age of the peasantry," when fifteenth-century survivors enjoyed a period of lower rents, higher wages, and a generally improved standard of living.[3] The marginal and total product of labor would have moved from point "C" to point "D," in figures 3 and 4.

[2] Dyer 1989:7, 133–34, 141; Hatcher 1977:262; Hilton 1975:213; Herlihy 1997:51.

[3] Van Bath 1963:10, 44; Dyer 1989:127–28, 144, 148–49 (and see his references to numerous studies of rising fertility on p.128); Bruce Campbell and Mark Overton have contested this point in the case of Norfolk (see Campbell and Overton 1993:38–105). However, they qualify their data on one point (which may have significant implications for the 1350–1500 period) by noting that yield sown per acre is not the same as overall agricultural productivity (output divided by area). See ibid.:67, 97–99; Mate 1993:47. As John Hatcher remarks of the general rise in living standards, " . . . To use the language of the economist, the real wage was a measure of the marginal produc-

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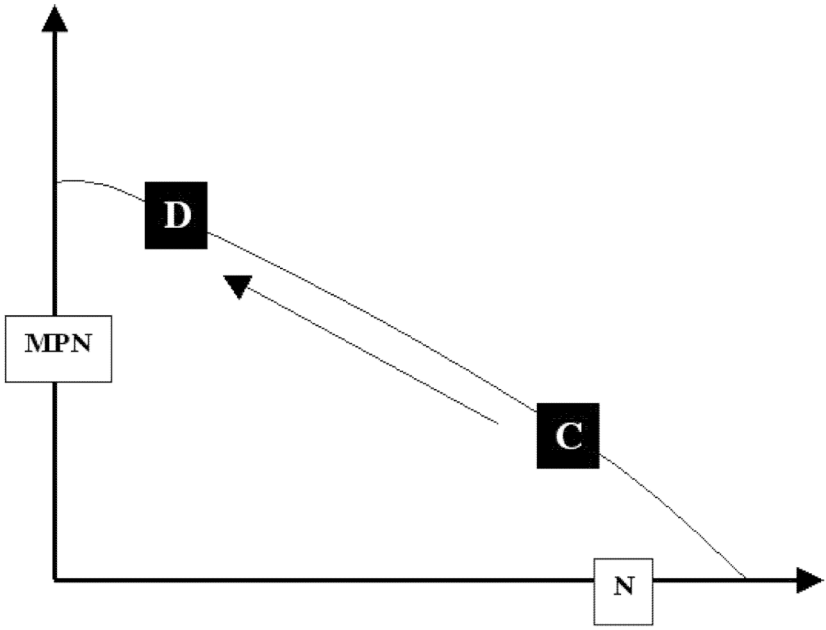


FIGURE 3. Showing the Marginal Product of Labor (MPN) with Decreasing Labor on a Fixed Amount of Land

All of this is old news to most historians and transparently simple to those who recall their basic economics courses. Disagreements among historians focus on the scale and scope of this contrast, and the role of other driving factors, such as class warfare from a Marxist perspective, and the role of commercialization, not on this basic economic pattern itself. My purpose here is not to enter into the larger debate surrounding the so-called "Postan" thesis, but rather to simply draw readers' attention away from this part of the economic model

tivity of labor, and this in turn must have been closely related to the welfare of the population at large" (Hatcher 1977:55; See Mayhew 1995:249–50. Note also his Table 1 (ibid.:244) where he shows a rise in per-capita income of modest proportions from 1300 to 1470, and near doubling of per-capita income between 1300 and the early sixteenth century. These figures should also be viewed, as Mayhew does on pp. 249–50, from the standpoint of "income expressed in terms of its power to purchase{{ellipsis}}goods" (see Dyer above) rather than monetary indices alone (adjusting for early fourteenth-century stagflation, the late fourteenth- and fifteenth-century excess of grain supply over demand which caused falling grain prices, etc. see Dyer 1989:41, 58, 66, 101–2, 113–14, 210, 220, 226, 227, 262–73). Adjusting for the supply of goods and services increases both the 1300–1470 and the 1300–1526 expansions in real per-capita income by a considerable degree. Compare this with his broader estimates for 1086, 1300, and 1688 and see his analysis of other recent estimates and extrapolations in idem, "Modelling Medieval Monetisation," pp. 57–68, 74–5, 195–96. See also Hilton1983:44; Lomas1998; Britnell 1993:160–64, 168, 184–85, 192; Miskimin 1985:29; Abel 1980:50–67; Kosminskii 1978:38–46; see Mayhew1995:248–51; and Dyer 1989:51–187.

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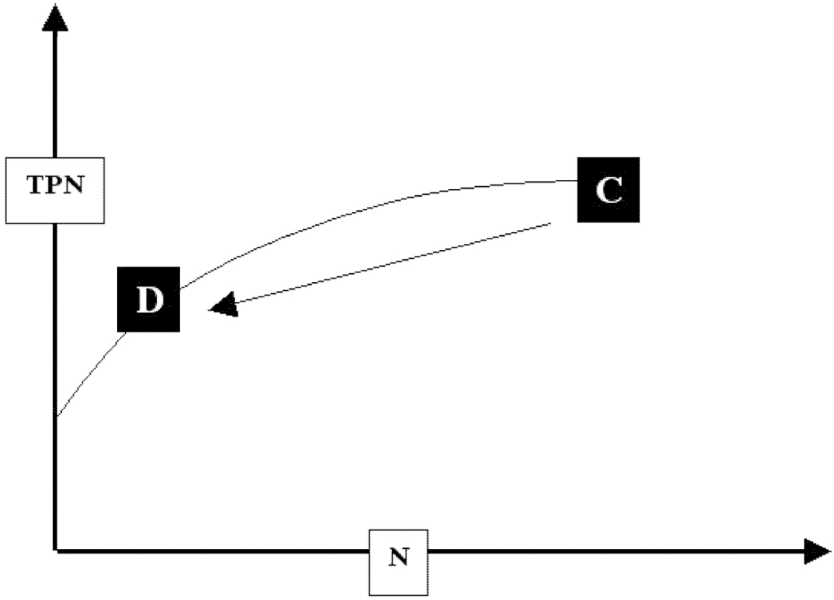


FIGURE 4. Showing the Total Product of Labor (TPN = Agrarian Output) with Decreasing Labor on a Fixed Amount of Land

and show how the "other half" of the graph functions. Scholars generally focus solely on the downward sloping section of the marginal product curve. In fact, many economic textbooks take diminishing returns as the starting point on the x-axis.[4] What is left unmentioned and largely unnoticed, because it so rarely applies to macroeconomies in the pre-industrial era, is that both curves are actually depicting *eventually* diminishing returns. That is, when the equilibrium point is pushed back far enough (towards a very low level of labor) the economy will find itself with positive marginal returns. At this low threshold of manpower, the labor is so scarce that, even with pre-modern agricultural "capital," each additional unit will yield more output than the previous unit (from points E to F in Figure 5).

Not surprisingly, it is hard to conceptualize the physical dynamics of this situation in pre-industrial history, except perhaps through reference to increasing commercialization and growing markets. The simplest way to visualize a tangible scenario like this for a medieval dry-farming regime is to view it on a microeconomic level and imagine one peasant trying to utilize 1000 acres of newly assarted land. In addition to the land, he has in his possession some primitive capital in the form of domestic animals and agricultural implements: a herd of

[4] See, for example, Krugman and Obstfeld 1991:40–45.

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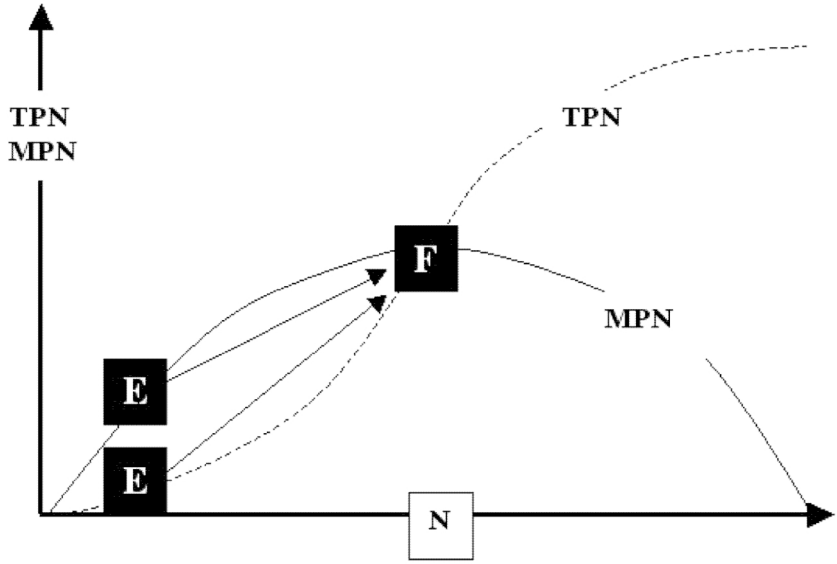


FIGURE 5. Positive Marginal Returns to Labor

pigs, an abundance of cows, oxen, horses, sheep, plows, carts, scythes, winnowing forks, and other miscellaneous goods needed for mixed husbandry. One peasant (one unit of agricultural labor) might be able to put much of the land to good use, especially if he let most of it to pasture. But imagine if a second unit of labor (a second peasant) were added to the existing land and capital. This additional peasant would, by employing the underutilized "capital" (agricultural implements), be able to devote more of the land to effective mixed-husbandry and increase the total output of the 1000 acres *by more than one hundred percent* (the increase shown here is 200%, from 1 unit to 3 units of produce, grain and pastoral), thus adding more to the total product than the previous unit of labor (on Figure 6).

This "synergy" would thus lead to *positive marginal returns to labor* with land and agricultural capital fixed. Eventually, as three, then four, and then five units of labor were added, we would reach a point where the more familiar diminishing marginal returns began to set in, and, as shown again in Figure 7, the MPN would begin to show *negative marginal returns to labor*.

The synergy for a dry-farming regime is thus most easily visualized if we picture it on a very local level. How it applies to the macroeconomies of dry farming is not the main concern here. The concept becomes one of cardinal importance, however, when we study the dynamics of irrigation economies.

Above a certain threshold of size, an irrigation system can potentially serve as an ideal archetype for examining positive returns to scale. If an irrigation net-

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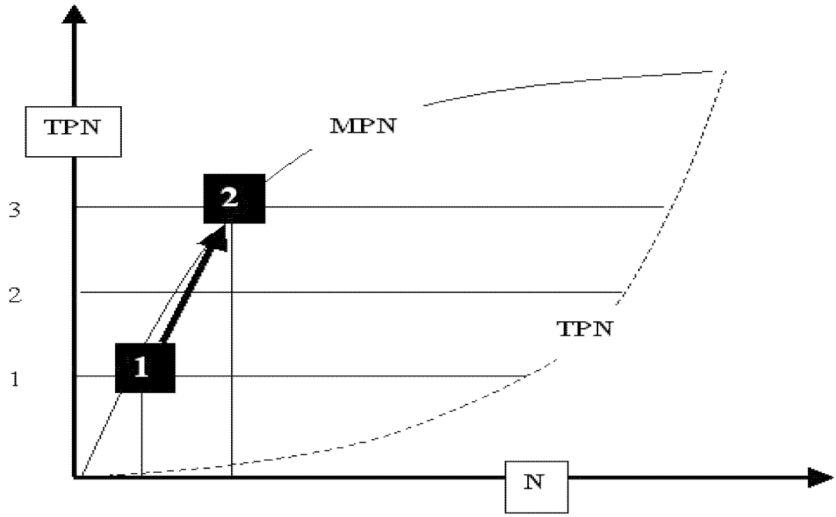


FIGURE 6. Positive Marginal Returns to Labor as one Peasant is Supplemented by a Second Peasant on 1000 Acres of Land

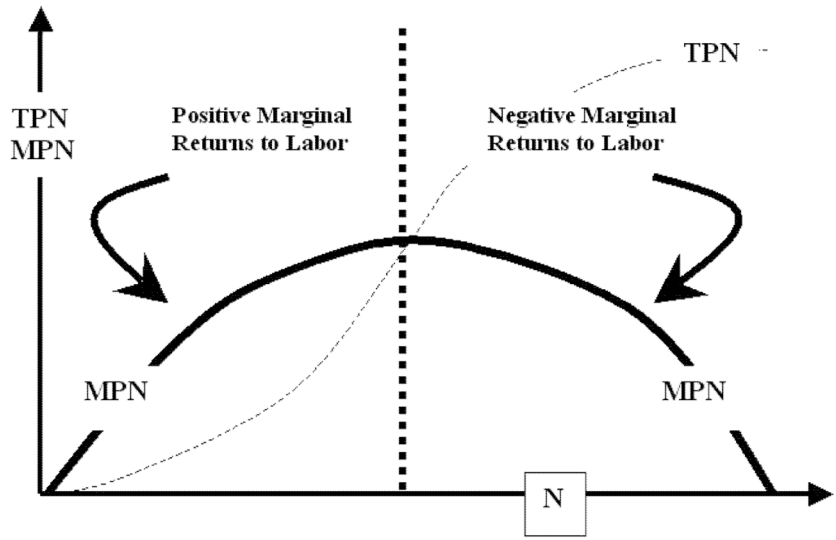


FIGURE 7. Positive and Negative Marginal Returns to Labor

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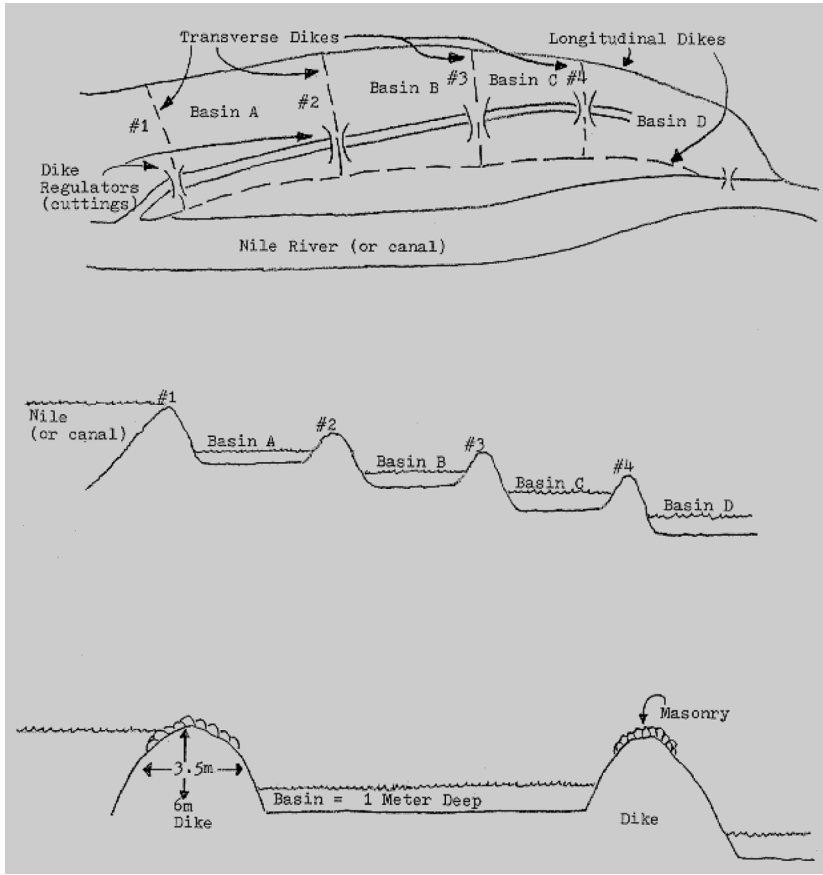


FIGURE 8. Basin Schematics (adapted from Willcocks 1889)

work is extended beyond the boundaries of local channels directly fed by a natural river, and larger interconnecting canals and dikes are used, the agrarian economy will then include an enormous element of capital (K) in addition to the usual labor (N) and land (L) that one finds in a pre-modern economy.[5] The modern production function can then be applied: $Y = A*F*(KLN)$, where Y equals total output, A is a coefficient of labor efficiency, and F is a constant, K is capital, L is land, and N is labor.

Take the example of Egypt's basin irrigation system in which transverse and longitudinal dikes trap floodwater from a natural river that feeds a man-made canal, shown in Figure 8.

[5] Abu Zayd 1987:15–20.

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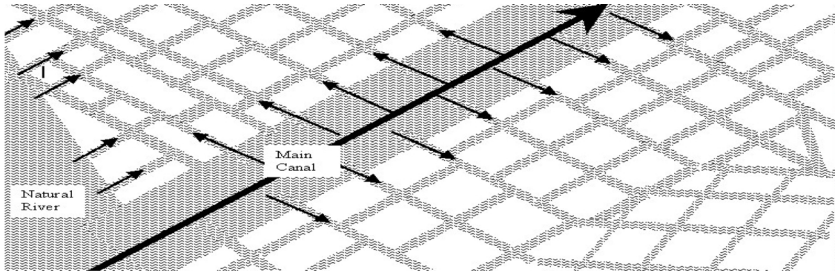


FIGURE 9. Village Basin Irrigation System with Main Canal Feeding Smaller Irrigation Canal

Seen from above, one can visualize a village irrigation system in which one large man-made canal feeds most of the village basins, while a few are fed by a natural river, as shown in Figure 9.

If, in this microeconomic scenario, labor (N) is reduced by a significant margin, more than 50 percent (for example) the villagers will no longer have enough manpower to keep the main canal and dike in working order and it will slowly decay as shown in the following figures 10–11. Egypt's basin irrigation system, like all hydraulic networks, has its own unique features. Every June, the Indian Ocean Monsoon brings a torrent of rain to the Ethiopian highlands. This enormous deposit of water then cascades down the Blue Nile and Atbara rivers, bringing with it an abundant supply of nutrient-rich topsoil from Ethiopia.[6] Prior to the construction of the Aswan Dam, this cascade of floodwater, combined with the equatorial flow of the White Nile, would inundate the Nile Valley and Delta, reaching a peak in September (in Cairo) before subsiding from October to November.[7]

Man-made canals of various sizes were then employed to draw this water away from the Nile and into flood-basins. Dikes were used to trap the water and to allow the moisture to sink into the basins before the sowing of seeds. The alluvium washed down from the Ethiopian highlands provided an annual supply of fertilizer that, in conjunction with the sophisticated crop rotation employed by the Egyptians of the Islamic era, guaranteed an annual seed-to-yield ratio of up to 1 to 10 for the winter crop.[8]

Egypt's irrigation system was divided into two levels of control: *sultani* and *baladi*. The *baladi* system functioned as the local network of dikes and canals for a single village, while the *sultani* system was a regional network of dikes and canals, divided by nomes ("provinces," Arabic: *ʿamal*), that linked the *baladi* systems together.[9]

[6] Popper 1951:87, 248, 250, 256; Willcocks 1899:230.
[7] Ibn Iyas 1995:101–4, 108–12; Ball 1939:162–77; Butzer 1976:59ff.
[8] Ibn Mammati 1943:259.
[9] See Toussoun 1925, particularly Planche XV for the province of al-Bahayra, based on al-Makhzumi.

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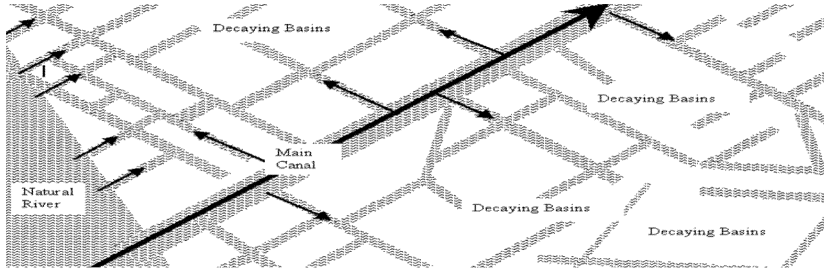


FIGURE 10. Decaying Irrigation System (Stage 1)

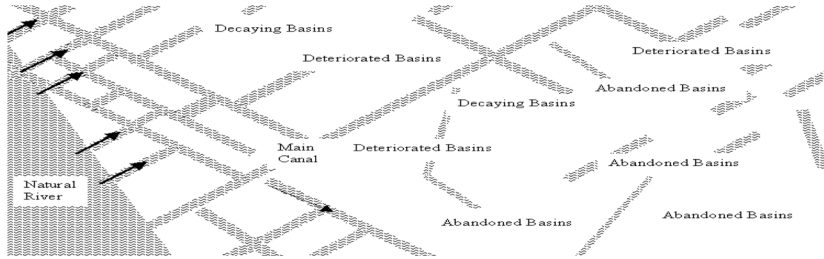


FIGURE 11. Decaying Irrigation System (Stage 2)

If the whole structure were struck with depopulation, *baladi* systems might continue to function smoothly for a while, but if labor was not used to maintain the interconnecting *sultani* systems, then all of the *baladi* systems not directly connected to a natural river or natural canals would begin to decay in precisely the fashion shown in Figures 10–11.[10] If population were not redirected and redistributed on the level of the *sultani* nome, the entire nome's irrigation network would begin to decay in the manner shown in Figure 5 (with the point of equilibrium moving from *F to E*), that is, the total agrarian output would decrease faster than population. The drop in Y (TPN), would be more than the proportionate drop in N in the equation Y=A*F*(K,L,N), because the capital was no longer being utilized (as in our example of one man in a thousand-acre plot). Of course, in this example, the capital would also be decaying, and the road back from point E to point F (in Figure 5) would require an extensive investment of resources in manpower over a fairly lengthy period of time.

[10] For Mamluk Egypt, see al-Zahiri 1894:128–29; al-Qalqashandi 1913–1919, vol. 3:515–16. For a broader discussion of irrigation repairs see, Rabie1972:59–90. For Ottoman Egypt, see Shaw 1962:61–63; and 1968:124.

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This macroeconomic scenario is exactly that which afflicted Egypt after waves of Yersinia pestis (Black Death) swept through this rich agrarian economy. Egypt's irrigation system during this period provides a nearly ideal example of positive marginal returns to scale on a macroeconomic level. First and foremost, Egypt was struck with tremendous ferocity by the Black Death. The fatalities from Yersinia pestis in Egypt were at least equal to those in England: half of the population had been eliminated by the early to mid-fifteenth century and the rural population was at least as heavily affected as the urban. Egypt thus provides a fascinating counter-test case for the pseudo-Malthusian pattern of England and many other parts of Western Europe. Secondly, its economic history in the fourteenth and fifteenth centuries is relatively well documented, something which cannot be said for many of the other irrigation systems in the Old World. Finally, Egypt's irrigation system was, at this period in history, controlled from the center (not from the nomes). This inhibited a regional, nome-level response to the crisis. Being controlled from the center, the system might have benefited from strong top-down management that controlled the crisis through redistribution of labor and redirection of 'public,' sultani, works, but the internecine warfare among the landholding elite was such that no central authority with a vested interest in the system as a whole came to the fore.[11] The irrigation system thus suffered losses in a sporadic, episodic, punctuated, and geographically variegated manner that effectively turned Egypt's regional (nome) system into a central-nodal system at the very worst moment.

The collapse of Egypt's agrarian economy was historically unprecedented. Egypt had never suffered such a loss and it is hard to imagine the depth of anguish the survivors of the plagues must have endured as Egypt's agrarian output fell by some 70 percent.[12]

Historical chronicles leave little doubt about this, as they extensively detail the sorrow in the countryside and the repeated waves of refugees streaming into major cities like Cairo to seek grain from the storehouses of the Sultan and his amirs.[13] Chronicles of the time also describe the slow disintegration of the irrigation system and the neglect of the regional, sultani networks.[14] Contempo-

[11] al-Qalqashandi 1913–1919, vol. 3:51–53, vol. 4:61–64, vol. 6:192–93; Tarkhan 1968:96–97; al-Maqrizi1853–1854, vol. 2:229; al-Zahiri 1894:113ff, 130; *Waqfiyya Raqam* (Endowment Number) 1019 *Wizarat al-Awqaf* (from the archives of the Ministry of Pious Endowments hereafter W.A.); 901 W.A.; 3195 W.A.; Petry 1983:188–89; Petri 1981:133, 145; Raymond 2000:168–69.

[12] The following numbers for "Agrarian GDP" were developed from cadastral surveys, chronicle reports, and late medieval state budgets. See Udovitch et. al. 1970:115–16; Darrag 1961:59–66; Toussoun 1924:153, cited from Ibn Iyas 1982, vol. 3:266; Shaw1968:21, 84–207; 1962:65.

[13] Dols 1977:163–65; Tucker 1981:215–24; Shoshan 1980:462–67; Lapidus 1969:11–14; ʿAshur 1993:45–46; al-Maqrizi 1957–1973, vol. 4:332; Raymond 2000:173.

[14] al-Maqrizi 1957–1973, vol. 4:564 in 824/1421, 618 in 825/1422, 646 in 826/1423, 678 in 828/1425, 709–10 in 829/1426, 750–753 in 830/1427, 806–809 in 832/1429, 834 in 833/1430, 863,874 in 835/1432, 903–904 in 837/1434, 831,950 in 838/1435; al-Maqrizi 1853–1854, vol. 1:101; al-ʿAsadi 1968:92–93; Ibn Taghri-Birdi 1930–1931, vol. 4:673; Ibn Iyas 1995:182; 1982, vol. 5:114–15, 124–25; al-Suyuti 1997, vol. 2:302.

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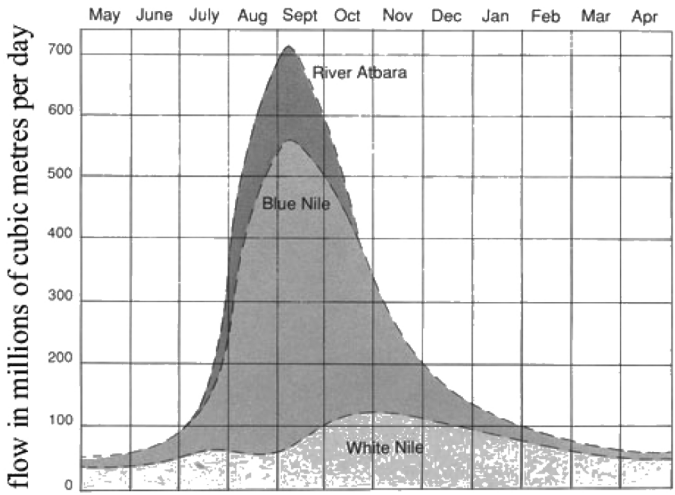


FIGURE 12. Nile Flood Peak as Measured at Aswan. (Courtesy of Michael Barron)

rary observers speak of famine gripping formerly abundant basins that had rippled with sheaves of wheat and undulated with rigs of barley. But the evidence for the loud death rattle echoing in Egypt's agrarian economy can be heard in more than just the vivid narratives of chroniclers, though their unanimity leaves little room for hermeneutic suspicion of literary topoi.[15] Other sources, such as cadastral surveys, revenue reports, and archival records from religious endowments, confirm the scale and scope of the decline, but they also tell us something more, something subtler that makes this horrific tragedy such a poignant case study even for someone engaged in cold economic analysis.

Egypt's price and wage scissors are exactly the opposite of what they should be. That is, if you were to look at Egypt for the standard picture that is found almost everywhere else—rising wages and falling grain prices—you would search in vain for this seemingly intuitive pattern. Like the mirror in Alice's looking glass, we find the whole picture reversed in Egypt. Wages fell dramatically after the Black Death, and grain prices rose.[16] Why did this happen? It seems to defy simple economic logic.

A large part of the answer lies again in the "other half" of the marginal product of labor curve. When we consider that we are dealing with underutilized/ruined capital (i.e., the sultani irrigation networks), we can see that we are moving from point F to point E on Figure 5. This brings us back to the point just stressed: the decrease in output was greater, significantly greater, than the de-

[15] Borsch 2000:131–45. [16] Borsch, in press.

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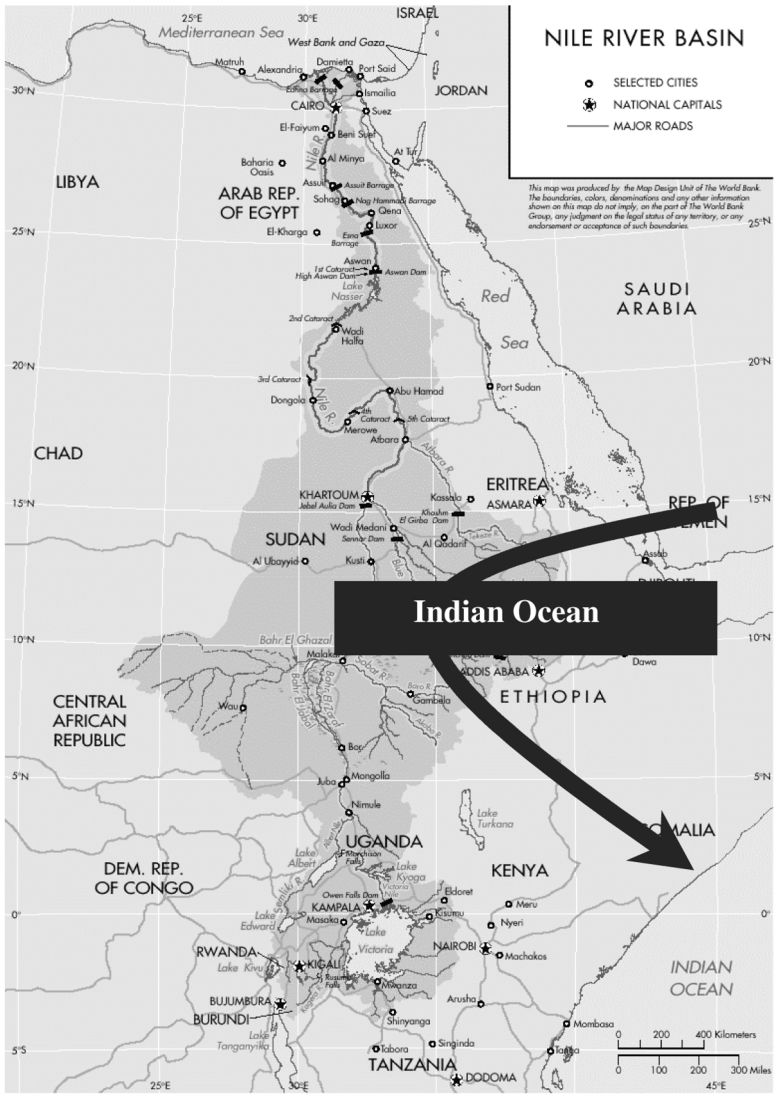


FIGURE 13. The Nile River from Tanzania to the Mediterranean

crease in population. The drop in output was so much greater than that of population that grain, not people, became the scarce commodity in the wake of a horrifying plague. This, combined with rural-to-urban flight, also helps to explain why people were *the relatively abundant factor* while grain, the largest commodity in Egypt's pre-modern economy, was the *relatively scarce factor*.

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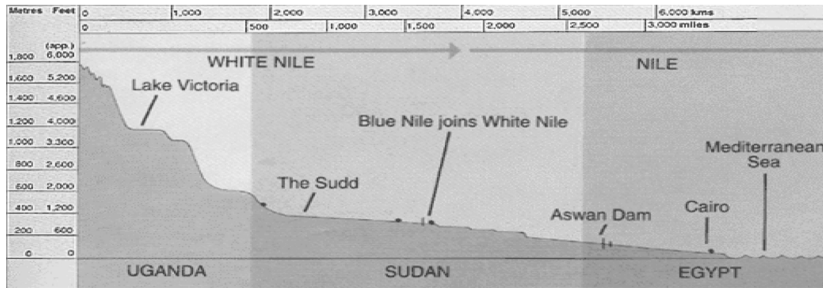


FIGURE 14. The Slope of the Nile River(s) from Tanzania to the Mediterranean

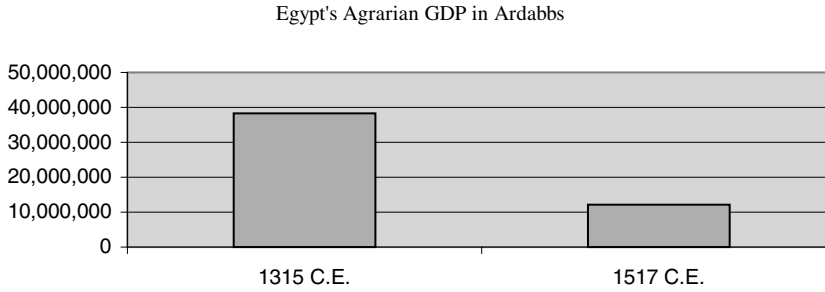


FIGURE 15. The Decrease in Egypt's Total Agrarian Output (=Y=TPN) (1 Ardabb = 165 Liters of Wheat)

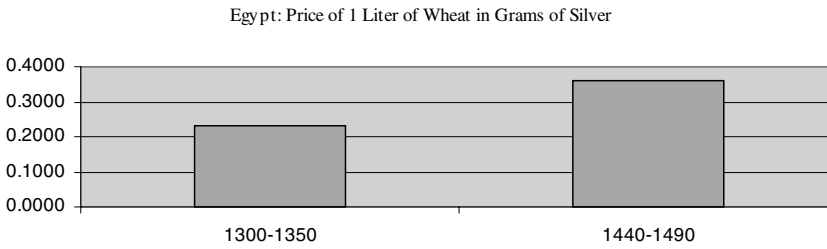


FIGURE 16. Prices of Wheat Before and after the Black Death in Egypt. (Courtesy of Michael Barron)

Or, to be more precise, capital (K), in the form of large canals that needed to be dredged with animal power, manpower, and simple equipment, and dikes that needed to be shored up with mud, straw, and a minimum amount of foundation stone, was now the *scarce factor* in the equation Y = A*F*(K,L,N), while both land (L) and labor (N) were *abundant factors*.

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Amidst the horrifying tragedy that Egypt endured we thus discern the principle that underlay many pre-modern irrigation systems: collapse, when it came, could have horrendous consequences that led to a known, but rarely applied, part of the marginal product curve—and in this curve may lie the answers to puzzling data from catastrophes that have struck irrigation systems in many other parts of the world throughout pre-modern history.

The application of this theoretical structure is all the more important for other pre-modern irrigation systems. Other irrigation systems were far more vulnerable than Egypt's. Egypt was blessed with a river that provided sediment and a relatively uniform annual flood.

Its basin system, catching the flood in the early autumn, was perfect for the planting of winter crops. Until the construction of modern dams, Egypt never had to face the historically disastrous problem of rising salinity, due to the slope of the Nile Valley and Delta, and the annual "washing" and draining provided by the September flood.

The same cannot be said for many other irrigation systems around the world. Basin and canal systems in other areas were far more troubled by problems of water damage and salinity buildup. For example, the Tigris-Euphrates system was active and interventionist and included a network of diversion dams that redirected the highly variable flood of spring snowmelt. The Tigris-Euphrates system required constant maintenance.[17] Canals had to be looped around to wash the salts out of the floodwater. Dikes had to be shored up continually to protect fresh plant shoots from becoming waterlogged.[18] Additionally, the Tigris-Euphrates system experienced exceptionally erratic and high floodwaters that led to periods when the system collapsed in toto.[19] If the data were available, an economic analysis of the effects of depopulation would be an ideal case study in economies of scale.[20]

Other examples can be found in many parts of the world: the Indus river valley, the Oxus river system in northern Afghanistan, and the Yellow river irrigation in China. The great Khmer civilization, with its intricate irrigation structure linked to the Mekong River, disappeared shortly after the Black Death, making this a particularly intriguing case to study. Most of these systems were far more vulnerable to collapse, and might be expected to fit this same economic profile if subject to depopulation. Many of these systems apparently did collapse, and this model might provide a means to understanding the fate of these cultures.

[17] McAdams 1974:1–6.

[18] Gibson 1974:7–20.

[19] Sears 1956:471–84; Eckholm 1976.

[20] The Tigris-Euphrates system had already been ruined by salinization and systemic breakdowns when Yersinia pestis pandemic struck Iraq. I am unaware of any available data or studies on the subject, but I imagine that the impact of depopulation on an already crippled economy was relatively mild.

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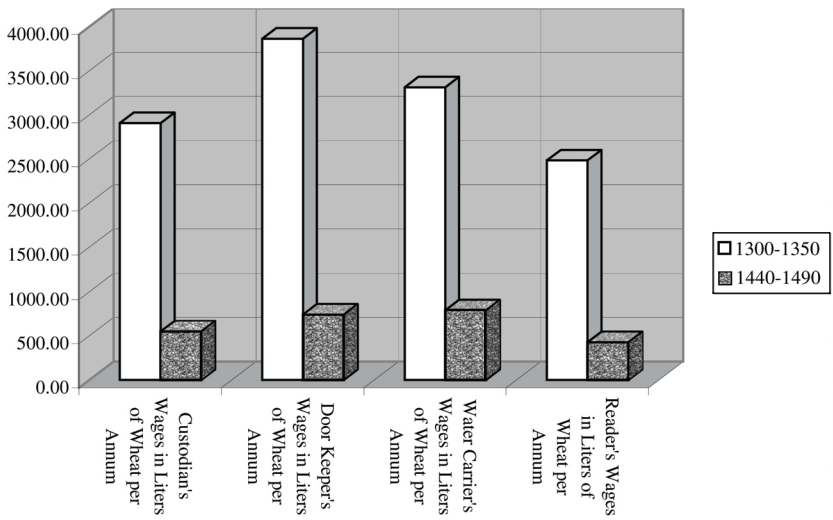


FIGURE 17. Wages in Egypt before and after the Black Death

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