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MODELLING SETTLEMENT STRUCTURES IN ANCIENT GREECE: NEW APPROACHES TO THE POLIS

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1. Introduction

> *Had he asked himself the obvious question: why did that particular apple choose that unrepeatable moment to fall on that unique head, he might have written the history of an apple. Instead of which he asked himself why apples fell and produced the theory of gravitation. The decision was not the apple's, but Newton's.*
>
> *M. Postan*

Thus, with a literary flourish and a dash of popular folklore, Postan implies that the difference between history and physics is not intrinsic to the subject matter, but the question posed of it. Provocatively put, this is an extremely tendentious point of view. Apples are mindless. On the other hand, people are not just minds and history is not merely the history of ideas. Human life is rich and complex, and to catch and illuminate its many dimensions many approaches are necessary.

These approaches are, in the broadest sense, disciplinary: anthropology, archaeology, geography, history and sociology all have as their subject people and society. Their concurrence is apparent in, for example, ethnoarchaeology (see eg. Binford 1983, and for anthropology and ancient history, Humphreys 1978), geoarchaeology (eg. Butzer 1982), historical geography (eg. Carlstein *et. al.* 1978, Pred 1981), historical sociology (eg. Giddens 1981, Abrams 1982, Skocpol 1984), and the Annales tradition (eg. Febvre 1922). In this paper we bring together history and geography in a new and exciting way.

The emergence and evolution of the Greek polis has a strong spatial aspect. It involved the formation of a community in a territorial unit encompassing a number of settlements, and the development of a 'capital' city. To have things in common, and in particular to share a common identity, presupposes a relatively intense level of interaction amongst those who constitute a community *vis-a-vis* those who are excluded from it. When the poleis were coming into existence, did discrete communities align themselves with those with whom they had most in common - those with whom they experienced the most intense interaction? Did location *vis-a-vis* other settlements have a significant effect on their affiliation and union?

What rôle, if any, did the spatial dimension play in the development of one settlement, rather than another, into the undisputed capital of the polis? What rôle, if any, did it play in the development of some cities into great cities? In particular, did location *vis-a-vis* other settlements, rather than location in a particular type of environment [1], have a significant effect on settlement growth and sociopolitical centralisation?

These questions can be explored through the construction of hypotheses on settlement interaction and growth in early Greece. The hypotheses can be rigorously evaluated by their translation into a mathematical model, which comprehensively tests those hypotheses in a simulation. In this paper we discuss such a project.

The mathematical model employed is one of a family of models developed over the last decade by a team of geographers at Leeds University; a programme of research and development in which the project here discussed represents the first attempt to apply the model principles and concepts in an historical context (*cf.* Clarke & Wilson 1985). Needless to say, like most pilot projects this one is prospective rather than definitive. But the results do suggest that this approach has some contribution to make toward an understanding of the ancient city. For a model embodies a set of hypotheses to explain the patterns it identifies, unlike most spatial analysis techniques (for a survey of which see Orton 1982). This model may also hold out the promise of a more immediate and pragmatic value for historians and in particular for archaeologists, namely a potential to identify relatively large or important sites on the basis of location alone.

Whilst the essential principles and ideas expressed in the model are fairly simple, the mathematics by which they are expressed is not. Therefore we shall attempt to explain what it does through analogies and simplifications; those for whom mathematics clarifies rather than mystifies the subject may find it helpful to consult the mathematical appendix and Rihll & Wilson (1987).

In the next section we discuss the model. We begin with some general comments on the nature of mathematical models and simulation (2.1) in order to clarify their aims and usage. We then discuss our model, describing in ordinary language what it is and how it works (2.2). Next we consider the data on which and with which it operates (2.3). The section concludes with a discussion of how the results are assessed (2.4). In section 3 we present some results which reproduce the general settlement structure of our survey area to a fairly high degree of accuracy, thus demonstrating that the simple hypotheses expressed in the model are sufficient to explain that structure. In section 4 we assess the value of the exercise (4.1), and suggest some of the main tasks for future research (4.2).

2. The Model

2.1 Models in general

A mathematical model consists of hypotheses concerning some real-world system of interest (in our case the settlement structure in Geometric Greece), which are formalised by mathematical equations. These equations allow the model to be quantitative and hence to be evaluated empirically, usually with the help of a computer. This process of experimental evaluation we may call simulation. It is a subtle process, both theoretically and practically.

It is subtle theoretically because the hypotheses and numerical data input to the model need considerable thought in their selection and interpretation. For example, a parameter like settlement importance is difficult both to define and to quantify. In historical contexts parameters and data are frequently difficult to quantify and when quantified are invariably estimates. Hence one must deal with a range of possible values, and consequently, as in any empirical work with a model, a large number of computations are necessary in order to evaluate variations in results as they are determined by variations in parameters or data. The outputs also present considerable and interesting problems of interpretation.

Simulation is subtle practically because obtaining input data can present problems. We have mentioned the problem of quantification. In addition, for analysing and interpreting settlement problems, scale is important; the number of settlements which need to be considered may be large, running into hundreds. This makes the use of computers essential, even if the mathematical models are extremely simple. The use of computers introduces further practical complications of course!

The purpose of a good model is to formulate simple concepts and hypotheses concerning them, and to demonstrate that despite their simplicity, they give approximate accounts of otherwise complex behaviour or phenomena. *If a model 'works'* (faithfully represents the known evidence) *then it shows that the assumptions and hypotheses built into the model contribute to an explanation of the phenomena.*

2.2 Our model

The aim of our model is to try to reproduce the settlement pattern in a fairly large area of central and southern Greece in the late Geometric period, using a small number of concepts and the small amount of data which is available. The basic concepts include site *size*, site *importance*, the *distance* between sites, and *interaction* between sites. Any explanation of an historical settlement pattern offered by the model will be *exclusively* in terms of these concepts and their hypothesised relationships.

The concept of interaction is modelled in a highly abstract sense; we make no assumptions about who or what is moving from A to B nor about its purpose. (The proper place for such conjectural details is during the interpretation of output, when the particular behaviour of the actors involved may be of concern.) The poleis and their predecessors were small societies coexisting side by side. By and large they spoke the same language, worshipped the same gods, and shared the same traditions as 'a people' (the nearest thing to a common history); interaction between them must have been relatively frequent. From sources of all periods we know that they begged, competed, fought, married, traded, travelled, worked and worshipped in, for or with other communities.

The hypotheses

Each site is considered as a place from which and to which interaction occurs. For clarity, a site is called an *origin zone* when it is considered as a place from which interaction originates, and a *destination zone* when it is considered as a place to which interaction is destined.

The basic hypotheses expressed in the model are that

(i) *interaction between any two places is proportional to the size of the origin zone and the importance and distance* from the origin zone *of all other sites* in the survey area, *which compete as destination zones;* and

(ii) *the importance of a place is proportional to the interaction it attracts from other places.*

We require for each site an index or measure of its size and of its importance: its size is associated with its rôle as an origin zone; its importance is associated with its rôle as a destination zone. For its size, population is intuitively reasonable and is relatively easy to quantify, albeit as estimates. For its importance, however, population is not necessarily appropriate. To take an extreme example, Delphi's importance was not related to the number of its inhabitants. We need a more abstract index of the importance or attractiveness of a place; therefore we use the concept of *resources*. This too is modelled in a highly abstract sense; even the basic distinction between allocative and authoritative resources is left for the process of interpreting the output [2]. Clearly, getting numerical data for these components can be theoretically or practically problematic. We discuss this below in the section on data, where a further hypothesis is adduced which defers the need to tackle these problems, and mollifies them. This hypothesis results in a special case of our model which we call *the egalitarian model*; this is the model we apply to Geometric Greece.

In order to 'fine-tune' the input data in the experimental evaluation of the model two further parameters are introduced, one of which relates to the distance between sites, the other of which relates to the resources available at a site. The former is used to simulate the ease or difficulty of communications, the latter to simulate the benefit or bane of a concentration of resources in one place [3]. These parameters are to be varied in the series of simulations. They are system variables, operating at the user-defined value right across the survey area. In varying them we seek an appropriate overall, or average, value.

Whilst we normally use these two parameters to vary the results, it simply is *not* the case that the model can produce any result one desires. To take an actual example, this model cannot reproduce in the same result a unified Attike and an independent Megara. The relatively vast polis of the Athenians can only be reproduced at parameter values which produce networks the size of regions, which is far too big a territory for a typical or even a large polis. Moreover, it is practically difficult (if not impossible) and more importantly it is theoretically invalid to try to manipulate the results to achieve some preconceived pattern [4].

We assume for the purpose of modelling the settlement structure that the survey area is absolutely level and that the distance between sites is the shortest (ie. straight-line) distance. This is a radical simplification of the real-world survey area and is completely counter-intuitive to historians trained to believe that the mountainous and fractured Greek landscape was in some way important to the development of the poleis. However, the actual landscape is to a large extent implicitly incorporated into the database through the location and density of settlements - none or few in mountainous or sterile areas, many or some in fertile and cultivable areas. It is nevertheless intriguing that this greatly simplifying assumption of an isotropic plain works as well as it does; all results discussed below assume it. In another application, we have modified this assumption (Rihll & Wilson, forthcoming).

The methods

These components and the hypotheses about their relationships are formalised and studied using mathematical methods known as *entropy-maximising methods* (see Gould 1972, Johnston 1979, 106-10, Thomas & Huggett 1980, 153-68, Wilson 1970). These methods are particularly useful in modelling types of social systems because they allow us to find the most probable *overall* state of the system whilst making the least possible assumptions about the particular actions and intentions of the people involved at the time. Entropy can be understood as an index of uncertainty - our uncertainty about the micro-level of the system being modelled, that is (in this case), the level of individual actors and actions. To maximise the entropy in a system is to maximise the possible configurations at the micro-level. The most probable overall state (or macro-state) is defined as that which results from the largest number of micro-states, of possible configurations.

For example, suppose that three people, A, B and C, move from place X to places Y and Z. If there are no constraints on the system - if, for example, places X, Y and Z are equidistant and Y and Z are equally attractive destinations - then each of eight different possible configurations, or micro-states, of A, B, and C's destinations are equally likely (see Figure 1).

Micro-states

	i	ii	iii	iv	v	vi	vii	viii
	Y Z	Y Z	Y Z	Y Z	Y Z	Y Z	Y Z	Y Z
A	1 0	1 0	1 0	0 1	1 0	0 1	0 1	0 1
B	1 0	1 0	0 1	1 0	0 1	1 0	0 1	0 1
C	1 0	0 1	1 0	1 0	0 1	0 1	1 0	0 1
	3 0	2 1	2 1	2 1	1 2	1 2	1 2	0 3
	1	2	2	2	3	3	3	4

Macro-states

Figure 1: micro- and macro-states

These *eight* different configurations or micro-states result in *four* overall states or macro- states: 1. All three people go to Y and none to Z (= micro-state i); 2. Two go to Y and one to Z (=

micro-states ii, iii and iv); 3. One goes to Y and two to Z (= micro-states v, vi and vii); and 4. None go to Y and all three go to Z (= micro-state viii). Macro-states 2 and 3 are more likely than macro-states 1 and 4 because 2 and 3 result from more micro-states.

However, there are constraints on the system: for example, the size of the origin zone, the importance of the destination zone, and the distance involved. These constraints effect the definitions of possible micro-states and thus the likely macro-states. If, for example, Y is nearer than Z to X, and a constraint is imposed on the total distance travelled, then in more complex situations with larger numbers of travellers, the number of feasible macro-states like 2 will outnumber those like 3.

Thus the most probable overall state is at the same time the one about which we can be least certain at the level of historical configurations of actors and actions. Entropy-maximising methods accommodate the idea that at any point in history there are many possible futures, and that what generally happens is the (unintended) outcome of a multiplicity of contingent human actions.

Terminals and networks

Interaction is calculated between each site and every other in the analysis (not just near neighbours) according to the hypothesis, each site being considered as an origin zone and then as a destination zone for every other site as it, in turn, is considered as an origin zone. (In fact the calculations are simultaneous, but the idea is essentially the same.) The total volume of interaction destined for a site may be called a site's *credits*. The volume of interaction which originates at a site - a figure which is constrained by the size of that site - we may call its *debits*. The largest single debit from a site can be compared with its total credit figure in order to establish settlement hierarchies. To be more precise:

> if site A's greatest single debit is to site B, and this single figure is more than the total of A's credits, then A is a lower order settlement than B.
> If site B's greatest single debit is to site C, and this single figure is less than the total of B's credits, then B is a not a lower order settlement than C,
> and B is called a *terminal*.

Whereas A's debit to its 'chief creditor' B is more than all A's credits, B's debit to its 'chief creditor' C is less than all B's credits. To illustrate this idea dramatically, consider the units of interaction as people migrating: then this is to say that there are more emigrants from A to B than immigrants to A from everywhere, and less emigrants from B to C than immigrants to B.

By plotting links between each site and its chief creditor, except *from* terminals, we can identify settlement networks, each of which has one terminal, one centre. This way of representing results is based on the ideas of Nystuen & Dacey 1961. We extended this procedure so that interaction between an origin zone and its other creditors, as well as its chief creditor, can be presented graphically. Single debits at or above a user-defined percentage of the largest debit from any origin zone can be plotted to reveal visually more of the information contained in the results. For example, suppose that interaction from A to B is calculated at four units, and interaction from A to C at three units (see Figure 2). If the user specifies that all debits at or above 75% of the maximum debit are to be plotted then links will be drawn from A to B and from A to C. Consequently the figures reveal that whilst the maximum debit from A is to B, there is also a relatively significant debit from A to C. Or one might want to set the percentage very low, to see how extensive, if attenuated, a particular site's influence is; at or above 25%, links will be plotted from A to B, C, D, and E.

Depending upon the scale and choice of the survey area (whether it is or is not a defined or definable territorial unit) a network may correspond to, for example, buildings within a settlement, settlements within a district, region or country, or settlements within a geographic area which is not coterminous with social or physical boundaries.

2.3 Our data

The sites

The survey area is part of central Greece; the period is the Geometric period. The area was chosen to include several major poleis about which a great deal is known to act as control sites, eg. Athens and Korinthos; two regions which are seriously neglected in the surviving documentary sources but which have recently received extensive archaeological attention (the Argolid and Boiotia); and the general area in which the earliest poleis are thought to have emerged (North-East Peloponnese). An extensive (but not exhaustive) search in 1985 revealed 109 sites within this area thought to have been occupied in the Geometric period (see Figure 3).

For each site to be included in the analysis we need to know its location, and that it was inhabited in the period under consideration. The inclusion of sites which were not settlements but sanctuaries (or at least are renowned as the latter, even if there is evidence for habitation in the Geometric period, as in the case of Nemea for example) calls for comment at this point. Any study of the emergence of Greek poleis requires a definition of polis, however vague. One of the most fruitful contributions to this debate was the suggestion that the construction of a temple should be considered the watershed between pre-polis and polis status (Snodgrass 1977). Not all temples were built in settlements: two of the earliest stone temples in our survey area, namely the Argive Heraion and the temple of Poseidon at Isthmia, lie several kilometres from any settlement. This is consistent with the idea that the polis and its settlement hierarchy emerged through the unification of smaller units (συνοικισμος), rather than by the outward expansion and domination of a preexisting principal settlement - originally at least [5]. These sanctuaries certainly attracted interaction; in some cases a considerable volume of it came from sites inside and outside the survey area [6]. Such sites should, therefore, be included in the analysis.

Indices

As stated above (§ Hypotheses), for each site in the analysis we require some figure to indicate its size and another to indicate its importance. In addition we require some figure to represent the ease or difficulty of communication across the survey area, and another to represent the benefit or bane of concentrated resources anywhere in the survey area. For ancient historians, this is a tall order. Even in the best documented cases we can often only guess at the size of the population in a specific period. It is even more difficult to find numerical indices of settlement importance, the ease of communication, and the relative merits of concentrated resources. However, whilst our model needs numbers, we can begin, with the help of an additional hypothesis, by estimating them within the model.

An additional hypothesis

In an extreme case we can start the simulation by assuming identical figures for the size and importance of each settlement and let *the model* determine distinctions between them by introducing a further hypothesis: that

(iii) *the size of a place is proportional to its importance* [7].

This relatively innocuous hypothesis in fact enables us to embed the entropy-maximising interaction model in a more powerful framework which allows site size and importance to be predicted [8].

It should be noted that by using the model in this way we can assume that *all sites were approximately equal in size and importance at the beginning of the period under consideration.* This assumption we will call *the egalitarian hypothesis* and when applied to our model we will speak of *the egalitarian model.* Historically, of course, the sites were not equal in size, but in any case this hypothesis seems more valid than one that the Geometric settlement sizes approximated the Classical, about which we know little more (see further below, 3 § Historical implications).

The egalitarian model

The egalitarian model has two major advantages with respect to the data. First, the model is clearly independent of the evidence used to test the results: no data on site size or importance goes into it! The model does not 'know', for example, that Athens was bigger and more important than Plataia; all it knows is that there was a settlement at a place in Attike and there was another at a place in Boiotia. Second, we can use the model with a very inadequate database; all one needs to know about a site to include it in the simulation is its location. (One can even speculate about its occupation in the period under consideration by experimentation; by adding a dubious site and comparing the results with those of experiments using the same parameter values but without that site.) This gives the model a practical potential to identify important sites at a local or regional level, even if evidence is currently lacking, or exists but has yet to be organised or utilised to bear upon the problem posed. More concretely, the model can predict that sites which appear to be undistinguished were important (according to the criteria employed; see 2.4 below) and, therefore, are worthy of closer investigation.

Thus by employing the egalitarian model we avoid the impossible task of gathering accurate quantitative data on the population and importance of the settlements investigated at the database construction stage. However, at the stage of testing and interpreting the results the same problem is just as acute, and apparently unavoidable. The output is necessarily quantitative, and approximate in the same way that the input data is approximate. But historical judgments about the importance of, say, Khalkis, Korinthos and Koroneia in the Geometric period are, and will probably remain, qualitative, based on more or less disparate quantities, qualities and types of evidence. We encounter the problem of assessing the model's results.

2.4 Assessing model output

As in any historical investigation of an hypothesis, we have an idea - perhaps only vague and certainly a tentative idea - of what it is we seek. Our model is designed to find the most probable *overall* settlement structure, and so it is ideas about the overall settlement structure in this area of Greece in late Geometric times which must be our guides.

Classification of sites

The sites in our survey area fall into three broad categories: (a) those 'known' to have been important in the period in question, based on the qualitative and disparate types of evidence known to us. Although different scholars may accord different emphases to different items of evidence, a consensus may be expected on a number of the 'most important' sites. In this case, we expect agreement on the inclusion of Argos, Athens, Khalkis, Korinthos and Thebes in the category of the, say, ten most important sites. (b) Those 'known' to have been unimportant [9] in the relevant period (debatable in the same way as the most important sites), eg. Aulis, Eutresis, Kreusis, Perakhora, Potniai, Schoinos, Zygouries. (c) Those which have been largely neglected by historians (ancient and modern) or archaeologists - the majority of the sites - whose relative importance is very difficult to ascertain. Amongst these are capitals of poleis or other territorial associations and a handful of individual settlements which were autonomous, at least for some of their known history, eg. Akraiphnion, Anthedon, Haliartos, Kleonai, Kopai, Koroneia, Lebedeia, Megara, Mykenai, Nauplia, Orkhomenos, Oropos, Phlious, Plataia, Sikyon, Tanagra, Thespiai, Thisbe, and large non-capital settlements such as Akharnai, Myrrhinous and Tenea. It is about the sites in this category that the model may make predictions, given its power to identify the more important sites in the survey area. For if a series of results is 'correct' for the majority of those sites and networks about which we have good information, then they are *probably* 'correct' for those sites about which we know relatively little. One practical application of the model is to use its results to direct further historical and archaeological investigation toward particular known and little known sites which are simulated as likely to have been more important than hitherto suspected.

Assessment of outputs

Intrinsic to the nature of modelling is the performance of a large number of simulations to establish a range of results worthy of analysis. In our model the parameters used to simulate the ease/difficulty of communication (β) and the benefit/bane of concentrated resources (α) are used both to search for historically significant settlement patterns and then to focus them. It may be helpful to think of this process as analogous to focussing a microscope, where one must search for biological structures of interest on the slide, and bring them into sharp focus for close examination. We systematically work through a range of different parameter values, locating those which give historically acceptable results, which we then focus through finer variation.

Crude and initial criteria for acceptance of a result of a simulation include

(i) a positive shortlist of control sites which we would consider to be the most important sites; category (a) above. We expect these sites to be amongst the most important of the hundred and nine in a simulation;

(ii) a negative shortlist of control sites which we would consider to be the least important sites; category (b) above. We expect these sites to be identified as unimportant in a simulation;

(iii) the correct identification of terminals, for we expect an emergent capital to be a terminal within a network;

(iv) the network should correspond approximately to the historical structure of that polis or territorial association.

Any results which are not sufficiently 'accurate' according to the above criteria are rejected.

Since the model finds the *overall* settlement structure which is *most probable* given the initial structure and the parameter values chosen, it is unlikely that any result will be 'correct' in every detail, even allowing for the lax definition of 'accurate' which we must employ. But if the settlement patterns and, in particular, the centres which emerge at different stages of centralisation of the survey area are quite regular, with only minor variations over a series of simulations using significantly different parameter values (eg. one or more settlements on the fringe of a network appear aligned instead with a neighbouring network, or isolated in their own territory; the centre shifts from one site to a neighbouring site, or becomes a subsystem centre in a larger network), then it confirms the probability of the basic structure, for it emerges as the most probable outcome even under different communication and resource conditions. That is why it is important to assess individual results as elements in a series of results.

A good result will identify as important sites the majority of those on the positive shortlist, and as unimportant the majority of those on the negative shortlist. In practice, in pioneering work of this kind and given the minimal input data, many scientists would be content with 40% accuracy. However, the data and the criteria by which they can assess accuracy are normally much fuller and more rigorous than we are able to adopt, and so we aim for 50% or better. If most of the positive control sites consistently appear in the ten most important sites and are identified as terminals or subcentres, and the negative control sites do not, then the hypotheses and assumptions expressed in the model are sufficient to explain the historical prominence or indistinction of those sites. If most of the networks consistently correspond to the historical settlement hierarchies at any one broad territorial level (eg. small, medium, large), then the hypotheses and assumptions expressed in the model are sufficient to explain the formation and structure of those networks.

Singular sites and networks

We then have to consider those sites and networks for which the same good overall results are in their cases 'incorrect' - particularly those for which the results are consistently 'incorrect'. A site's result may be incorrect in one of two ways: it may be simulated to be more important than the record suggests, or it may be simulated to be less important than the record suggests. It is rather more complicated for an incorrect network, which may be simulated to be more extensive, more intense, less extensive or less intense than the record suggests.

There are five possible reasons for consistently incorrect results for a site:

(i) the model is insufficient to explain that site's historical prominence/indistinction;

(ii) the input data for each site is inadequate. The egalitarian hypothesis must be abandoned and differentials in site size at the beginning of the period in question must somehow be reflected in the input data;

(iii) the prominence/indistinction of that site as it appears in the historical or archaeological record is exaggerated/underrated [10];

(iv) the area in which the site lies has been unusually thoroughly surveyed/neglected relative to neighbouring areas or the survey area as a whole, so that there are disproportionately many/few known sites in that area;

(v) a site's prominence may derive from its position in a network which is, in our terminology, local, regional, national or global. If its historical prominence derived from an area larger than or outside the survey area then it may not perform as well in simulation as it is expected to do. In such a case the extent to which it falls short of expectations in simulation may indicate the extent to which it attracted interaction from outside the survey area.

There are also five possible reasons for consistently incorrect results for a network:

(i) the model is insufficient to explain that network's extent or coherence;

(ii) as for sites;

(iii) the extent or coherence of that network as it appears in the historical record is exaggerated/underrated;

(iv) as for sites;

(v) the topography of that area cannot be ignored. Either the barriers are so great or the routes so easy that some modification to the assumed isotropic plain is necessary to 'correct' the distances between sites inside and outside the area in question.

For any particular site or network reason (i) may be elaborated by known historical circumstances; for example, frequent or intense interaction between two sites may have been conducted most often under arms. Until resolved (if ever) there may consequently have been a fiercely observed, if mobile, border between the sites in question which is not explained by the model and consequently not reflected in the results. The most obvious example of this in our survey area is Khalkis and Eretria. Other examples in different survey areas would probably be Mantinea and Tegea, or Elis and Pisa.

3. Results

We now consider some results, recorded in Figures 4 to 7, starting with a relatively devolved structure and proceeding towards a more centralised one. As stated above, we only consider results which are acceptable according to the criteria in 2.4 (§ Assessment). In particular, we will not normally discuss sites appearing on the positive or negative shortlists, as satisfaction of the criteria for the majority of those sites is a prerequisite for acceptance of a result. Therefore most of the discussion will concern category (c) sites - those whose relative historical importance is uncertain, and singular sites and networks.

The legend for each figure gives the parameter values which produced the result: the smaller the β value, the easier communication across the survey area is simulated to be; the larger the α value, the greater the benefit of concentrated resources is simulated to be. Small β or large α tend to produce centralised structures; large β or small α tend to produce devolved structures. Also given is the number (Tn) of terminals (and therefore networks) predicted; this acts as a rough guide to the degree of centralisation in the survey area as a whole. The legend also carries the percentage of the largest single debit from any origin zone at or above which debits are plotted from origin zone to destination zone. The best compromise between a desire to see overlapping spheres of influence or dependence both within and between networks and a desire for clarity is 75%, so most figures conform to this standard. A site's maximum debit determines to which network it belongs (unless it is a terminal); such links are marked with an arrow where confusion could arise. This allows us to sketch the approximate line of the boundary between networks, even in relatively densely settled areas. The predicted rank of terminals, and occasionally other high-ranking but non-terminal sites, is given on the plot in larger figures (the small figures are the site numbers).

Consider Figure 4. It shows thirteen networks. Given that all sites have identical input data, except their locations of course, and no modifications to the isotropic plain have been made, it is remarkable that even at this low level of centralisation the model should identify among the most important sites in the area Khalkis, Athens, the Argive Heraion, Thebes, Nauplia and Koroneia.

We also seem to have three 'near misses'. Nisaia is the simulated terminal instead of Megara just to the north. There may be several reasons why the terminal identification here is consistently incorrect, but the most obvious would seem to be our ignorance of this area and the relatively tiny number of known sites (reason [iv]). Koukouvaones is simulated to be the terminal in the area of Akharnai, where current hypotheses would prefer to see Menidi, just to the west; the identification is not secure but is based on the number of inscriptions concerning Akharnai found in the churches and houses of Menidi (Eliot 1976, 6). Finally Kromna is identified instead of Korinthos, just to the west: this is particularly interesting. Since Roebuck's paper in 1972, reconciling the achievements of early Korinthos with the site of early Korinthos has been a well publicised problem. Kromna, situated approximately half way between Korinthos and Isthmia, is as yet unexcavated. Extensive residential remains were discovered in 1960, and large cemeteries nearby: it was a substantial settlement. The sherd-scatter suggested that it had been occupied for about a thousand years, from at least the seventh century BC to the fourth AD. Sporadic excavation over three days in 1938 turned up nine poros sarcophagi (amongst other things), and a single grave excavated in 1960 contained some 26 vases of fine quality closely dated to 560 BC [11]. Perhaps the collection of villages which was 'Korinthos' in the early colonising period (Roebuck 1972, 101-3) was more dispersed than commonly assumed. This site is predicted regularly by the model as an alternative to Korinthos in the company of Athens, Thebes, and Argos or the Heraion, and some investigation of the site and environs may prove worthwhile.

Another apparently anomalous 'important' site, Ay. Io(a)nnis, is hardly known. It possesses a huge fortress, larger than Tiryns (Hope Simpson 1965, 118), but has not yet been excavated. Koropi (ancient Sphettos) likewise is little known. One of the original twelve to synoikise with Athens (Strabo 9.1.20), it is the provenance of one of the most luxurious Geometric vases ever found (the Stathatou amphora, Coldstream 1977, 133).

Koroneia's network is somewhat anomalous. Koroneia is regularly simulated to be the terminal in a network stretching broadly north-south from Orkhomenos to Thisbe and Khorsia. She was an independent and fairly important state, and interacted frequently with Orkhomenos - often under arms. And whilst she seems to have preserved her independence into Classical times, perhaps in alliance with Lebedeia and Haliartos [12], it was Thespiai, rather than Koroneia as in the simulation, which managed to subdue Thisbe when she did not retain independence (ie. between

447 and 379 BC [13]). This erroneous network seems to be a consequence of the boundary of the survey area (which is a specific and drastic case of reason [iv] for incorrect networks), for the interests of Orkhomenos, situated right on our north-west boundary, went principally to the north and west, to Phokis and Thessaly, rather than to the south and east. The survey area is in Orkhomenos' case unfortunate and produces misleading results, both for herself and, to a lesser extent, for Koroneia: it would be interesting to compare the results with those of a survey area encompassing Phokis and Lokris (East and West).

Note the position of Nauplia before we leave this result. A member of the Kalaurian Amphiktyony, Nauplia is shown here as the terminal in a network of sites spanning both sides of the Argolid Gulf, including Asine, Tiryns, and Hysiai in the Thyreatis. If we lower the β parameter to simulate easier communications we see, in the next result (Figure 5), that Nauplia is still a terminal but in a much reduced network consisting only of herself, Pronaia and Asine on the eastern bank [14]. Nauplia's loss is Argos' gain - not the Heraion's; Argos is now identified as a secondary centre in the network. Historically, Argive territory extended down the west bank to Hysiai at least by c.669 BC when the Spartans there suffered a heavy defeat (Paus. 2.24.7). The Messenian Wars seem to have given the Argives cause or excuse for conflict with the communities in this southern Argolid network (later legend has it that Argos supported the Helots and then the Messenians, whilst Asine and Nauplia were allies of Sparta [15]). Argos ultimately defeated or subdued them; the Asinians around 710 BC (Coldstream 1977, 154, 163), and Nauplia during the latter half of the next century. Although the sources [16] - which are very late - say that Nauplia was sacked and her people, like the Asinians, evicted, modern scholars are skeptical. Her history henceforth is meagre, but archaeological evidence suggests that she "continued to exist, and possibly to flourish" (Tomlinson 1972, 44; see also 77). Not surprisingly the simulation fails to account for the fall of Asine, but suggests that the Nauplians' strength (relative to their neighbours) was their strategic position - strategic at least until the development of Temenion.

Other things to notice in comparison with the previous result (cf. Figures 4 & 5) is that easier communications produce three systems less; two less in Attike and one less in Boiotia. The network centred on Athens now incorporates that whose centre had been near Akharnai; unification in the north of Attike produces one very dominant centre, Athens. Unification in the south of Attike, however, produces two nearly equal and neighbouring centres. The centre in the Mesogeia is pulled ESE from Koropi to Merenda (ancient Myrrhinous), and just to the south there is a secondary centre, only slightly less important, at Kalyvia (ancient Prospalta). Merenda, the new terminal, has an impressive archaeological record for Geometric times. Two vases reckoned with the Stathatou amphora as the most luxurious of their time were found here (Coldstream 1977, 133) and to date three cemeteries have been excavated: one described as "vast" and another which has produced (amongst other things) an archaic kouros and kore (Leekley & Noyes 1976, 19).

In the Korinthia we see a similar dual foci pattern emerging. Kromna's influence is clearly diminished with the emergence of Korinthos as a secondary centre. Kleonai (site no. 88) also deserves attention in this region. A subregional centre of an east-west network in Figure 4, Kleonai is in both results united with the Argive network (although interaction between herself and Korinthos is quite strong; ≥ 75% of the chief debit) which is consistent with her historical loyalties and, interestingly, contrary to the geography, ie. *topography* of the area and the relative *distances* involved. This somewhat surprising historical alliance, reproduced in the result, has been noted by Tomlinson (1972, 29) and Adshead (1986, 4f, 35), who offer a political explanation. Note also in this respect Krommyon (site no. 77), which the simulations always unite with the Korinthian network. According to Strabo (8.6.22) Krommyon was in Korinthian territory, though once belonged to Megara. Pottery and burial practices of Geometric date have been found to be almost wholly Korinthian (Coldstream 1977, 85f., Salmon 1984, 25, 48), and there are no extant finds dated earlier than c.800 BC. This inevitably raises a question mark over the accuracy of Strabo's information. On the other hand we know very little of Megarian burial practices, or indeed, of anything Megarian in the Geometric period, when she is known better for her settlements abroad than in her homeland [17].

The western sector of the Theban network has a subordinate centre at Thespiai (site no. 30), serving as the regional centre over Askra, Eutresis, Kreusis and Siphai. Thespiai was a large and independent state until Classical times; her decline was synchronous, not coincidentally, with the rise of Thebes. Her territory included Askra, Eutresis, Kreusis, and until c.386 Siphai (which gained independence only for a short time). According to Herodotos (5.79.2) Thespiai was a close friend of Thebes and had long been so, though presumably was not by 423 when Thebes destroyed her city walls [18].

In the north of the survey area Akraiphnion is simulated to be a very important site. This is particularly interesting in view of the fact that, though long known to archaeologists, it has become a familiar name only recently. The cemeteries began to receive serious attention in 1974, and were quickly recognised as one of the most exciting discoveries of the decade in Greek archaeology. After one season some 400 richly furnished graves had been excavated, containing over 2000 vases from Attike, Euboia and Korinthia, as well as from other areas of Boiotia. By 1986 the total number of graves revealed was in excess of 1100 [19]. The excavations and finds still await proper publication, so a detailed comparison with other sites is not yet possible, but this figure can be roughly compared with that of *dated* graves in Athens *and* Attike between c.1000-500 BC: 1,226 (Morris 1987 Appendix 1). Had Akraiphnion not recently received this attention, which it clearly deserves, the model results would have suggested it as a prime site for investigation.

Whether its performance in simulation is accurate in historical terms remains to be seen. Evaluation need not be confined to the city (not yet excavated) however: the Ptoion, about two kilometres east of Akraiphnion, calls for consideration here. Excavated intermittently by the French School for over a century, this double sanctuary (to Apollo Ptoios and the hero Ptoios) is well known. It very suddenly burst into life c. 640-620 BC. The imposing dedications, which include numerous marble kouroi and kourai, bronze tripods, plaques and statuettes, suggest that the Archaic period was one of great prosperity in this region, and that the sanctuary was one of great importance (Schachter 1981, 52-73). By identifying Akraiphnion as one of the most important late Geometric settlements, the model goes some way to explain the 'unheralded' and dramatic development of the Ptoion sanctuary in the Archaic period.

Figure 6 shows the effect of increasing the simulated benefit of concentrated resources; the ease of communication is simulated to be the same as in Figure 5. This change in conditions has scant effect in the northern half of the survey area, but causes a small number of significant changes in the southern half, including the absorption of two networks into larger neighbouring networks.

Korinthos, Kalyvia and Argos benefit most from the different circumstances, in terms both of overall rankings (Korinthos 9 $\rightarrow$ 1; Kalyvia 10 $\rightarrow$ 3; Argos 11 $\rightarrow$ 4) and of becoming the terminal in their respective networks (cf. Figures 5 & 6). Nisaia and Nauplia suffer most, losing independence as their networks are incorporated into Athens' and Argos' respectively - Nisaia does retain secondary centre status, however. Kromna and Merenda also do much less well in the different circumstances of the simulation, losing terminal status and rank importance in their respective networks. The Argive Heraion remains an important centre but becomes subordinate to Argos.

Elsewhere in the survey area the settlement hierarchy and structure remains much the same, except that Thespiai loses subordinate centre status. Negligible changes in overall rankings occur and a handful of sites are aligned instead with neighbouring networks: Eleon with Thebes instead of Khalkis, Askra with Akraiphnion (via Medeon) instead of Thebes (via Thespiai), Siphai and Kreusis with Koroneia instead of Thebes (via Thespiai), Spata with Athens instead of Merenda, and Kleonai, Zygouries and Tenea with Korinthos instead of the Argive Heraion. Note that half of these sites (Eleon, Askra, Spata and Zygouries) are simulated to interact at least 75% as much with their former network as they do with their present one.

The overlapping and competing spheres of influence which the model simulates are revealed by plotting more of the debits for the same result, which also helps to explain the changes in more detail. This is done in Figure 7, which shows the same result as Figure 6, but all of the simulated interaction debits from any origin zone (except terminals) which are 25% or more of the maximum debit from that origin zone have been plotted. Border zones are stippled where interaction goes over the border to a site in a neighbouring network; the density of the stippling is determined by the number of borders crossed (the maximum number is three, in the areas of Siphai [site no. 34] and Pagai [site no. 43]).

Almost all borders are fuzzy. Consider the Megarid which, whilst not identified as an independent network at these parameter values, is identified as an area of complex affiliations. Although its major interaction is simulated to be with Athens, at least 25% of that volume goes to Korinthos, and at least another 25% goes to Thebes. By plotting other percentages we are able to calculate that about 55% of the interaction from Nisaia goes to Athens, and about 20% each to

Korinthos and Thebes. When an origin zone's interaction is dissipated like this, it would suggest that, unless some very powerful interests intervene, such a site's attachment or commitment to any particular terminal would be correspondingly weak. This also illustrates how the model simulates a large centre some distance from the origin zone attracting more interaction than a small site much nearer to it: it is the more distant terminals, Athens, Korinthos and Thebes which attract interaction from Nisaia, whilst Nisaia attracts between 25 and 49% of the maximum debit from the closer but less important sites on the borders of their networks, Eleusis (site no. 73) and Krommyon.

The spheres of influence of the six highest ranking terminals at these parameter values are summarised in Table 1. The complex relationship between the number of sites and the intensity of interaction in determining a terminal's (and any site's) rank importance is clearly indicated here. Khalkis' priority over Thebes arises from the greater *volume* of interaction attracted to Khalkis, albeit from a smaller number of sites, than is attracted to Thebes, albeit from a larger number of sites. The maximum debit from an origin zone can vary from, theoretically, 100% of the interaction leaving it to 40% or thereabouts, and a 100% credit from a small site may be less in volume, and therefore less significant, than a 20% credit from a large one. To complicate matters further, a subordinate centre may compete with the terminal for interaction from sites in and out of the network; it may also extend the territory of the network to which it belongs.

These effects are made more apparent by tabulating such subsystems separately, see Table 2. The subordinate centre Nisaia attracts maximum debits from three sites and brings them into the Athenian network, thus extending it west. But these sites' interaction debits go to Nisaia, not to Athens, and do not contribute directly to Athens' importance [20]. The relationships between Medeon and Akraiphnion and between Siphai and Koroneia are similar. In the Argolid, however, the Heraion is clearly a competitor of Argos for interaction from sites in the north and mid Argolid (also demonstrated in simulations which identify it rather than Argos as the terminal).

Historical implications

The model simulates settlement growth through a series of iterations from an initial egalitarian state: the hypothesis is that initially all sites are approximately equal in size and importance. Interaction between them is first simulated on the hypothesis that it is related to the distance between each site and every other. (Since at this stage all the sites are equal, the size of the origin zone and the importance of the destination zone are irrelevant.)

The communications parameter (β) determines the radius of any site's effective influence. The number of sites within that radius, combined with their proximity to the site in question *and* to all the other sites in *their* radii, determines the volume of interaction which arrives at the site. This gives a total credit figure for each site. The differential credit figures are then used to assign input values of size and importance for each site in the next iteration; ie. the results of the first iteration are used to set the input for the next. Consequently in the second iteration the interaction hypothesis takes account of the (hypothetical) size of the origin zone and the (hypothetical) importance, as well as the distance, of the destination zones.

The degree to which the results are considered historically accurate is the degree to which these hypotheses are sufficient to explain the historical settlement structure. In answer to our original questions, the results show that location had a very significant effect on settlement affiliation and union in the formation and development of poleis; on the development of the capital; and on the development of some capitals into 'great' cities. The relative importance of Athens, Korinthos, Argos, Thebes and Khalkis in the historical period need not be 'explained' by the supposition, implicit or explicit, that they were always (or at least, in the period *before* the period under consideration) relatively important: it can be explained largely by their location *vis-a-vis* other Geometric period sites. The sites in the survey area patently were not approximately equal in size in the early Geometric period. However, the fact that the egalitarian hypothesis reproduces the historical structure of the late Geometric/early Archaic period reasonably well suggests that those differences in size were not significant in political development, and it demonstrates that the historical structure can be largely explained without reference to them.

The Mesogeia area of Attike is the only outstanding error, where the simulations consistently predict the emergence of an important centre. Two reasons immediately present themselves to explain this error. First, the series of results shows that, whilst Athens is consistently identified as the terminal in the north Attike network, the terminal in the south Attike network is variously Sphettos (site no. 57), as in Figure 4, Myrrhinous (no. 58), as in Figure 5, or Keratea (no. 59), as in Figure 6. Historically there may have been considerable competition between these sites for dominance in the area, which weakened the influence of each, whilst Athens' influence was unconstrained by any effective competitor in her area. This could conceivably underlie the second reason: that when the Athenians synoikised, they chose Athens as their 'capital'. In this case it would be interesting to compare the results with those of a survey area which covered the Archaic period, as a strong settlement produces its own penumbra of subordinate settlements. An important further experiment would be to see whether the inclusion of input data on late Geometric/early Archaic site size and importance would better reproduce the historical settlement structure than the egalitarian hypothesis.

The period of analysis is important, since in Boiotia, to take another example, the early league (if 'league' is an appropriate word for the loose and informal grouping which it seems to have been) evolved in the sixth century, and the strong league with Thebes at its head was not in operation until about 447 (Demand 1982, 16-20). In order to model that settlement structure the sites in the survey area should be those of Classical, not Geometric, date.

4. Concluding remarks

4.1 Evaluation

There are basically three kinds of benefit to be gained from building a simulation model (Aldenderfer 1981).

1. *Conceptual.* Model building demands explicit structure and a clarity which forces one to rethink current concepts and assumptions, and to do so at the start of the exercise. It was at this stage, for example, that the weaknesses in the concepts polis and 'city' became painfully apparent. The problem had to be redefined; this redefinition involved the employment of the concepts of site *size*, site *importance*, *resources*, *terminals* and *networks*.

2. *Developmental.* This is the benefit arising from trying to translate a verbal hypothesis into a mathematical model, or, as in this case, trying to simplify and generalise a mathematical model and the verbal hypotheses it expresses to suit a society, space, and time very different from that for which it was originally developed. Either way, the process forces the model builder to give clear and sharp expression to his or her ideas and the relationships between them, and to work through the hypotheses in a consistent and coherent manner.

3. *Output.* This is the benefit which may arise if the model has been successfully tested and the results may be expected to be realistic, that is, usable. This model seems to have predictive power, but it cannot be demonstrated until sites which are consistently simulated by the model to be important, notably Akraiphnion and Kromna, are excavated.

The major benefits of model building at this time are, we believe, in the conceptual and developmental areas. Stale or inappropriate concepts, unfounded or unjustifiable assumptions, poorly formulated or poorly grasped hypotheses, gaps in knowledge or data, are all brought into sharp focus in the attempt to build a model, irrespective or whether or not it ultimately 'works'.

A model directs attention not toward *what* happened, but to *why* it happened. The aim is to construct a set of simple hypotheses which emphasise significant features of the system under consideration and which, when rigorously pursued, reproduce what happened. Our model has emphasised the features of space and interdependence; the interdependence of settlements within a polity and of polities within a region. We have emphasised space by initially and literally making 'all other things equal'. We have emphasised interdependence by making the differentiation of all other things dependent on interaction across space. The hypotheses in our model are simple, general, and abstract; the explanations it can offer are in consequence general and abstract. They aim to be sufficient, not complete, explanations of the norm, the trend, without which the peculiar and the remarkable in history cannot be appreciated.

Our apparent disregard for so-called 'urban theory' is based not on disciplinary parochialism or rampant empiricism (*cf.* Finley 1985, 61-6), but on the futility of the majority of this difficult and often sophistic literature for students of ancient society. For a city does not exist independently of the society which produces it, and urban studies tend in consequence to be about society as a whole. The attempt to identify distinctively 'urban' phenomena (now abandoned) amounted to an attempt to identify a distinctively urban type of society, and problems with the definition of 'urban' left only the sort of societies traditionally studied by anthropologists out of the reckoning. (It is symptomatic of the field that in recent theoretical work what is properly called 'the sociology of consumption' continues to go by the name of 'urban sociology' in order to preserve intellectual continuity with earlier studies! Saunders 1985, 289) Less ambitious theoretical and empirical work continues on types of city (and society), principally four types: the primary city (or 'first cities', eg. Adams 1966, Wheatley 1971); the medieval city (eg. Hohenberg & Lees 1985, Holton 1986); the contemporary city in post-industrialised nations (eg. Berg 1982, Saunders 1985); or the contemporary city in underdeveloped or developing nations (eg. McGee 1971, Reissman 1964). In each of these cases significant features of ancient society (such as those mentioned below, 4.2) are largely or wholly absent, and the emphases are instead on features alien to and largely inappropriate to ancient society.

We have considered the city not as an urban form but as a locus of social interaction, a place where allocative and authoritative resources are concentrated and focussed; our concern has been with the whole scatter of settlements rather than with the known centres (see Finley 1983, 5f). Our model takes account of the theoretical desideratum to consider a polis not as a closed community, isolated in space and time, but as an open community interdependent to greater or lesser degree on other contemporary communities. Poleis were autonomous societies - or tried to be. But however much they disliked the fact, they were not independent, and they knew it: a common way of canvassing support when under threat was to point out the consequences of the plaintiff polis' defeat for other poleis - both for those which threatened it and for those which might support it (eg. Thuk. 1.32-36; 1.120-24).

We believe that this approach begins to realise settlement archaeology's great potential for understanding social process and change (Snodgrass 1984, 229, more generally Snodgrass 1987).

4.2 Future research

One of the most important tasks ahead in this kind of research lies in the construction of models (mathematical and non-mathematical) of other aspects of the ancient city, or more broadly, ancient settlement. This is necessary to identify more constraints which could be introduced into this model to produce an even better correspondence between the simulated results and the 'facts' as we know them, and thus to refine the hypotheses expressed in the model and the explanations it can offer. Very significant and distinctive features of ancient society which are pertinent include: land ownership as a correlate of citizenship, where citizenship was neither universal (before AD 212 in theory at least) nor trite; 'hinterland' - however tiny - as a correlate of settlement - however tiny; and scale: polities huge by the standards of the time and the culture, such as Athens, which covered an area tiny by our standards - in this case smaller than the West Riding of Yorkshire [21]. We need to construct a model to explain the size of networks or poleis: why c.70 sq. miles was the average size, and why some poleis were significantly smaller or considerably larger than this.

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1. One could reasonably argue that the former subsumes the latter. An emphasis on settlements rather than on the landscape on which their residents live allows a more abstract approach and produces a model which is more widely applicable.
2. Allocative resources are *material* resources deriving from man's dominion over nature; the environment, physical artifacts and technologies. Authoritative resources are *non-material* resources deriving from the dominion of some people over others; the capability to organise and coordinate other people's activities. See Giddens 1979, 100f; 1984, 258-62, also 143f.
3. 'Communications' is a very general concept covering both the means and the networks by which resources are transported from A to B. The resources in the real world may be, for example, people, goods or information; carried by foot, donkey, cart or ship. The network may be, for example, footpaths, roads, rivers or coastlines. 'Easing' communications in the simulation corresponds to real world improvements in the safety or convenience of movement brought about by, for example, peace, the partial or total elimination of bandits or pirates, better roads, or quicker or more reliable transport.

   Resources are concentrated at sites. Examples of allocative resources are foodstuffs, tools, arms or buildings; examples of authoritative resources are leaderships of social organisations such as kinship groups, military units or administrative groups. 'Increasing' the benefit of concentrated resources in a simulation corresponds to real world political or economic advantages of large quantities of foodstuffs collected and stored at a centre, for example; or to political, economic or religious advantages of a large number of visitors to a shrine. It favours sites proportionally to their importance.
4. It is probably impossible to alter significantly the 'performance' of one site without causing equally significant and probably undesirable side-effects on any other site, as the performance of each is interrelated to the performance of every other. We have experimented with this sort of manipulation and can assure readers that, partly because of these unpredictable side-effects, results are much better when the model operates on the egalitarian hypothesis (see 2.3).
5. For speculations on the rôle of non-settlement sanctuaries in the evolution of the polis see de Polignac 1984. One could argue that typically settlements incorporated by conquest were not considered part of the polis but subordinate to it, as seems to have been the case for some of the settlements in the Argive plain and was certainly the case for the Spartan perioikic communities.
6. Dedications and debris at the Argive Heraion, for example, peak during the Geometric and Archaic periods, after which they very suddenly decline, see Waldstein 1902, especially 39;

Mason 1976, 90 for summary. This suggests that its importance, in terms of attracting interaction from elsewhere, was greatest at this time.

7. This hypothesis obviously requires a feedback loop in the program.
8. *Cf.* Harris & Wilson 1978, Wilson 1981, and the mathematical appendix below.
9. It is difficult to identify somewhere as definitely unimportant because most sites are poorly served by surviving literary evidence and an archaeologically uninspiring site is not likely to be excavated - those which are tend, for several and delicate reasons, to be sites which were important in another period.
10. This is a knotty problem. Consider the archaeological and literary evidence on Sparta, for example, which may have been a puzzle had not a passage of Thukydides survived: Suppose, for example, that the polis of Sparta were to become deserted...(1.10.2) What Thukydides did not predict was the capacity of *literary* evidence to mislead later generations merely by its unrepresentative production and survival, irrespective of the degree of bias of its content.
11. Wiseman 1978, 66. Wiseman 1976, 470 for summary; also Salmon 1984, 24, 35, 156.
12. Hell.Oxy. 11.3; translation and commentary of § 11 (the Boiotian constitution) is conveniently available in Moore 1983, 127-34. See also Thuk. 4.93.4, and Roesch 1965, 37f.
13. Hennig 1974, Roesch 1965. Thisbe had a common border with Thespiai and Koroneia, Strabo 9.2.29.
14. Note that the parameter reflecting the benefit of concentrated resources (α) is also lower (ie. less benefit) in this result.
15. According to Pausanius (4.27.8, 35.2) the Asinians and Nauplians were allowed to continue to live in their new settlements (New Asine and Mothone) in Messenia after its liberation; from this we deduce that their pro-Spartan stance did not extend to subjugation of the Messenians, at least in living memory.
16. Strabo 8.6.11; also Paus. 2.36.5; 3.7.4; 4.24.4.
17. Legon 1981 for regional survey; Biers 1976, 565 for summary; also Genière 1983.
18. Roesch 1965, *ibid.* 1976, 101; Fiehn 1936. The Cambridge/Bradford Boiotia Expedition estimate the size of Thespiai at 140 ha., *AReps* 1986/7, 23f. See also the fuller account in Bintliff & Snodgrass 1985.
19. Cf. *AAA* 7 (1974) 325-38; 10 (1977) 273-86; *AReps* 1974/5, 18; 1975/6, 16; 1980/81, 22. The 1986 figure was reported to me by Steve Hodkinson (pers.comm.).
20. They contribute to Athens' importance only in so far as they make Nisaia a relatively large site on the first iteration, and this in turn makes Nisaia's debit to Athens in the second iteration more voluminous than that from a site at the same distance but simulated to be of smaller size.
21. Since the territorial home of the citizens of a polity and the subordinate territories of an empire should be distinguished, this applies to a substantial part of Roman as well as Greek culture.

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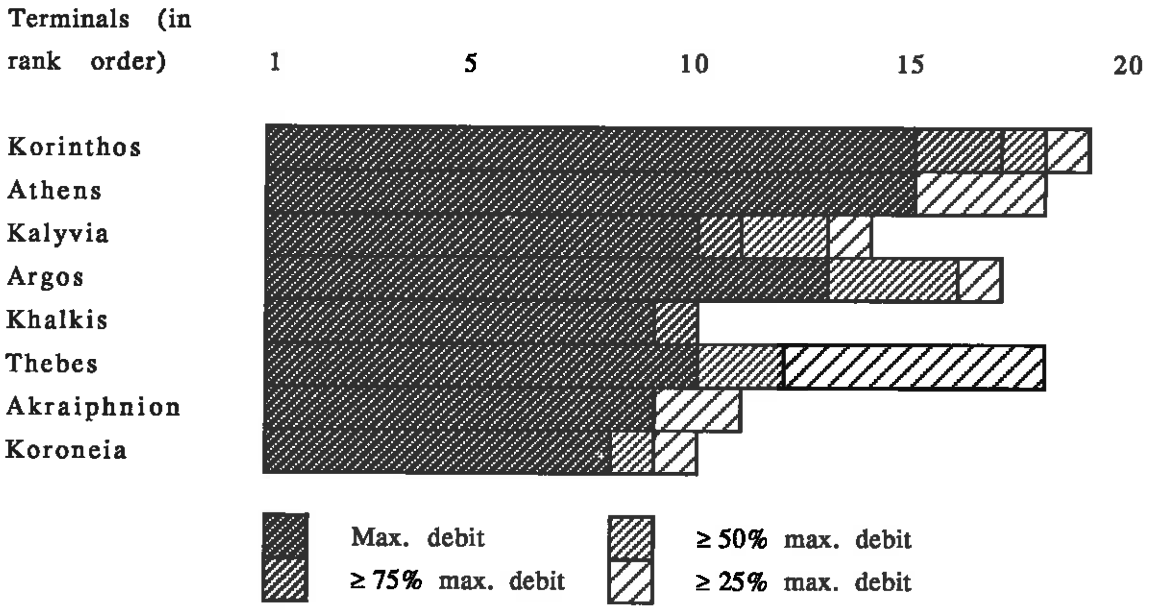


Table 1 No. of sites over which terminal exercises influence

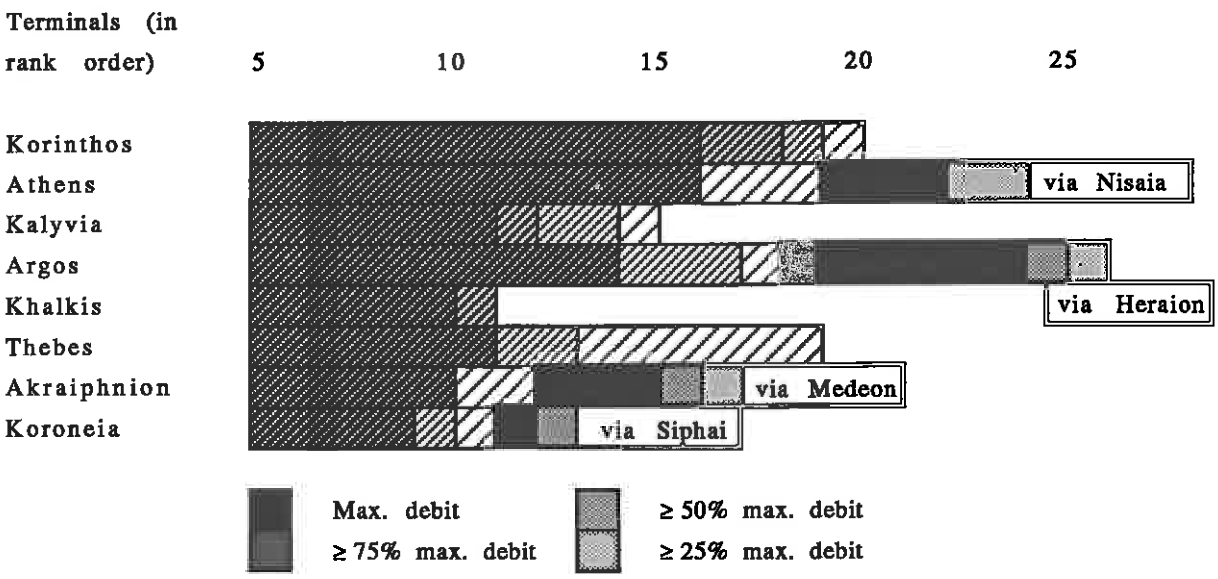


Table 2 No. of sites over which terminal exercises influence (indirectly)

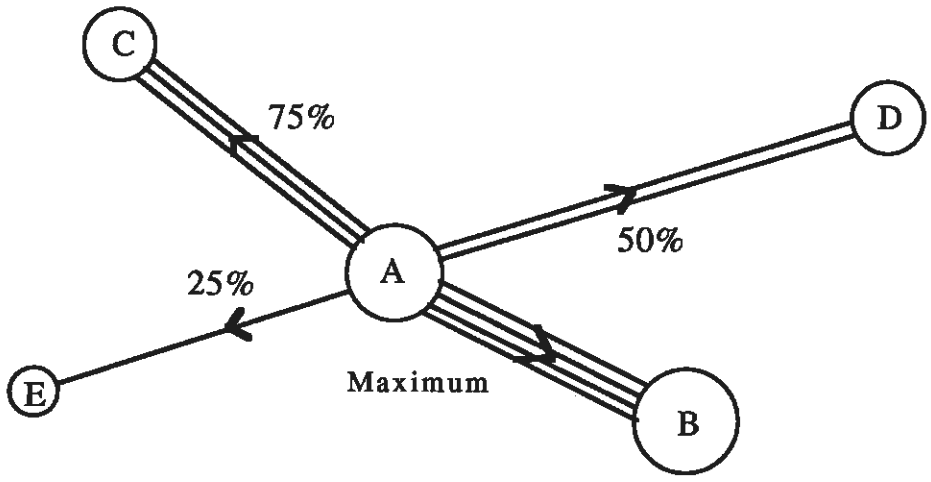


Figure 2 Proportion of maximum debit

Figure 3: The survey area

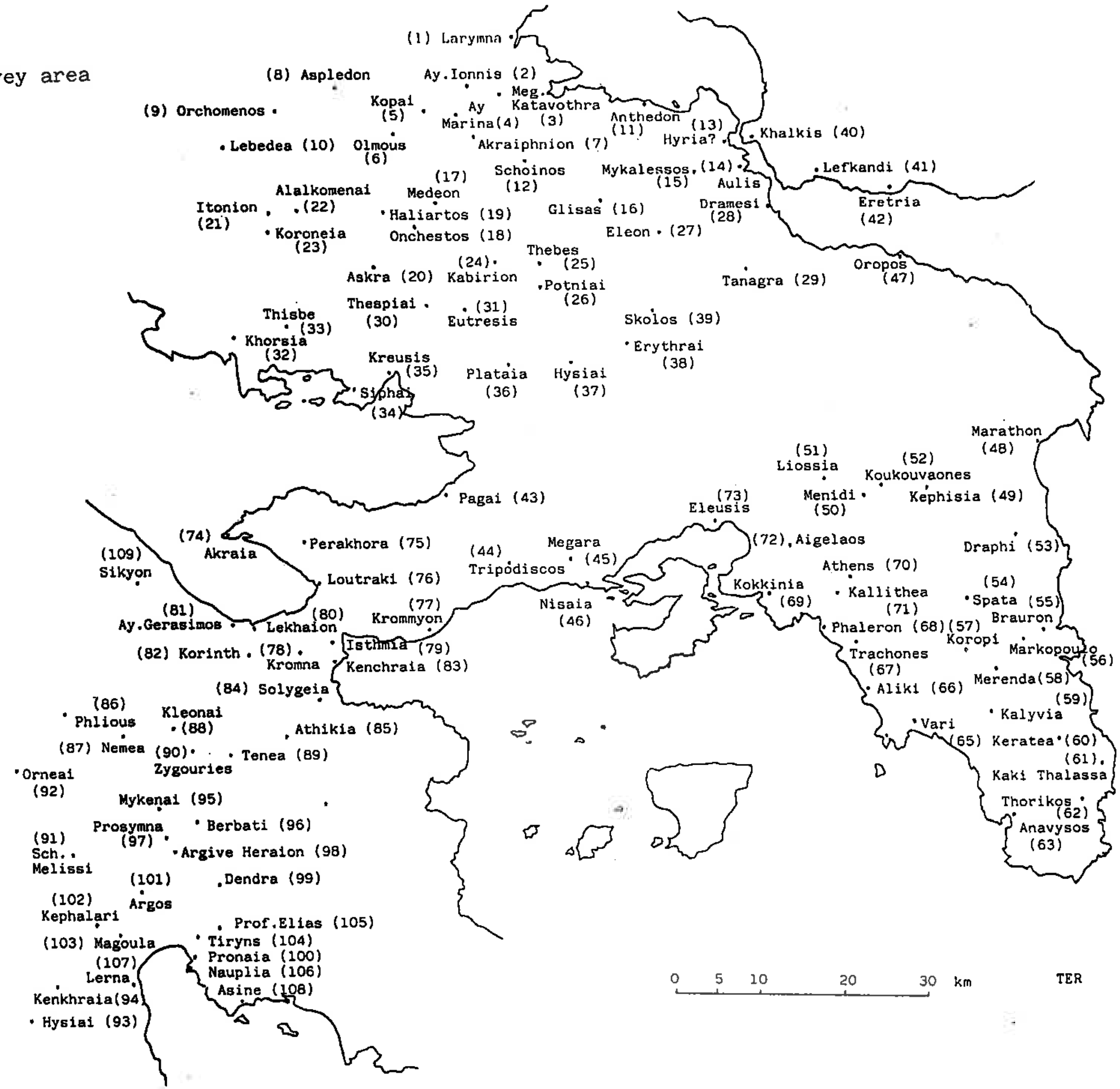


Figure 4: $\alpha = 1.025$

$\beta = 0.25$

$T = 13$

$\geqslant$ 75% max. debit

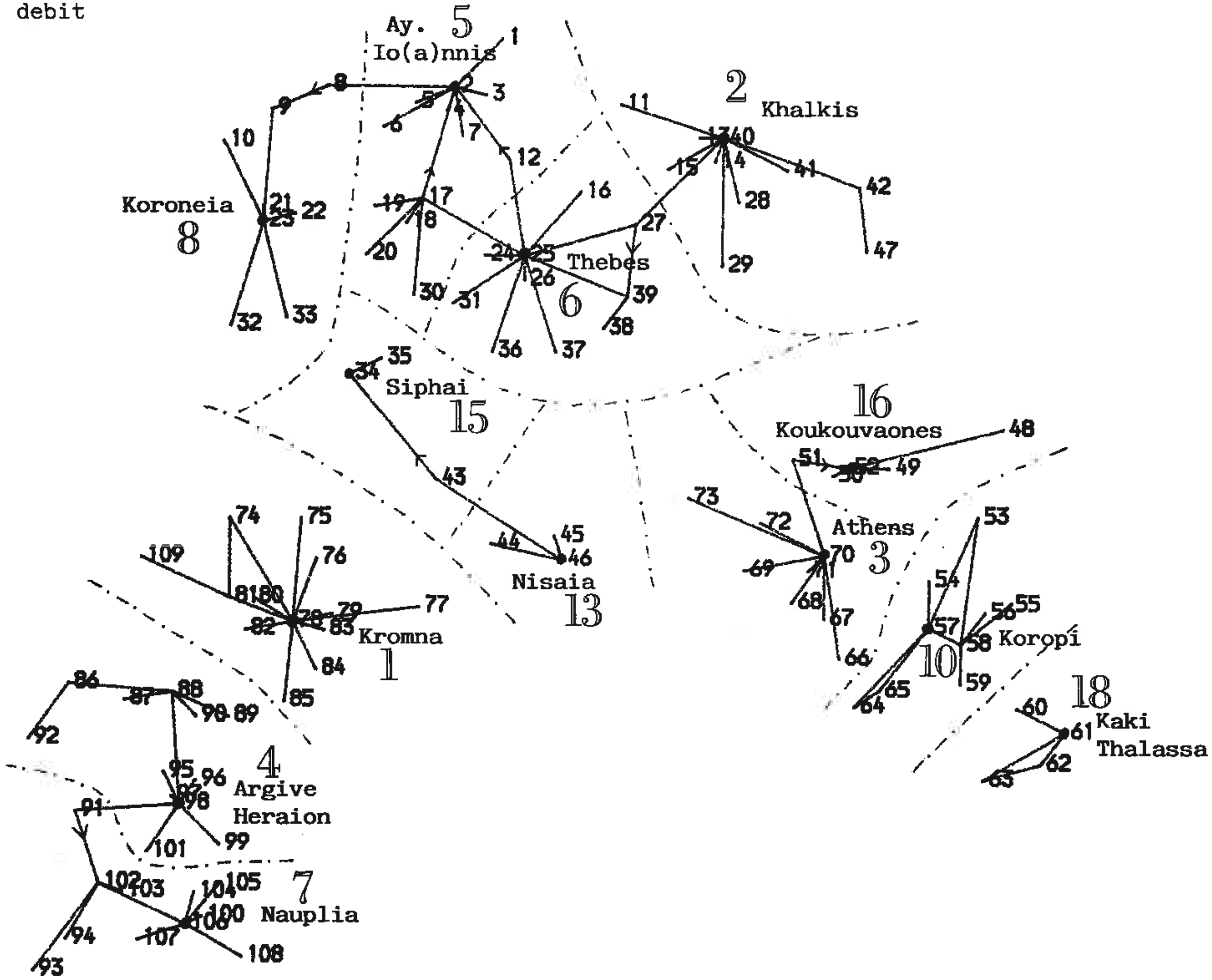


Figure 5: $\alpha = 1.005$

$\beta = 0.175$

$T = 10$

$\geqslant$ 75% max. debit

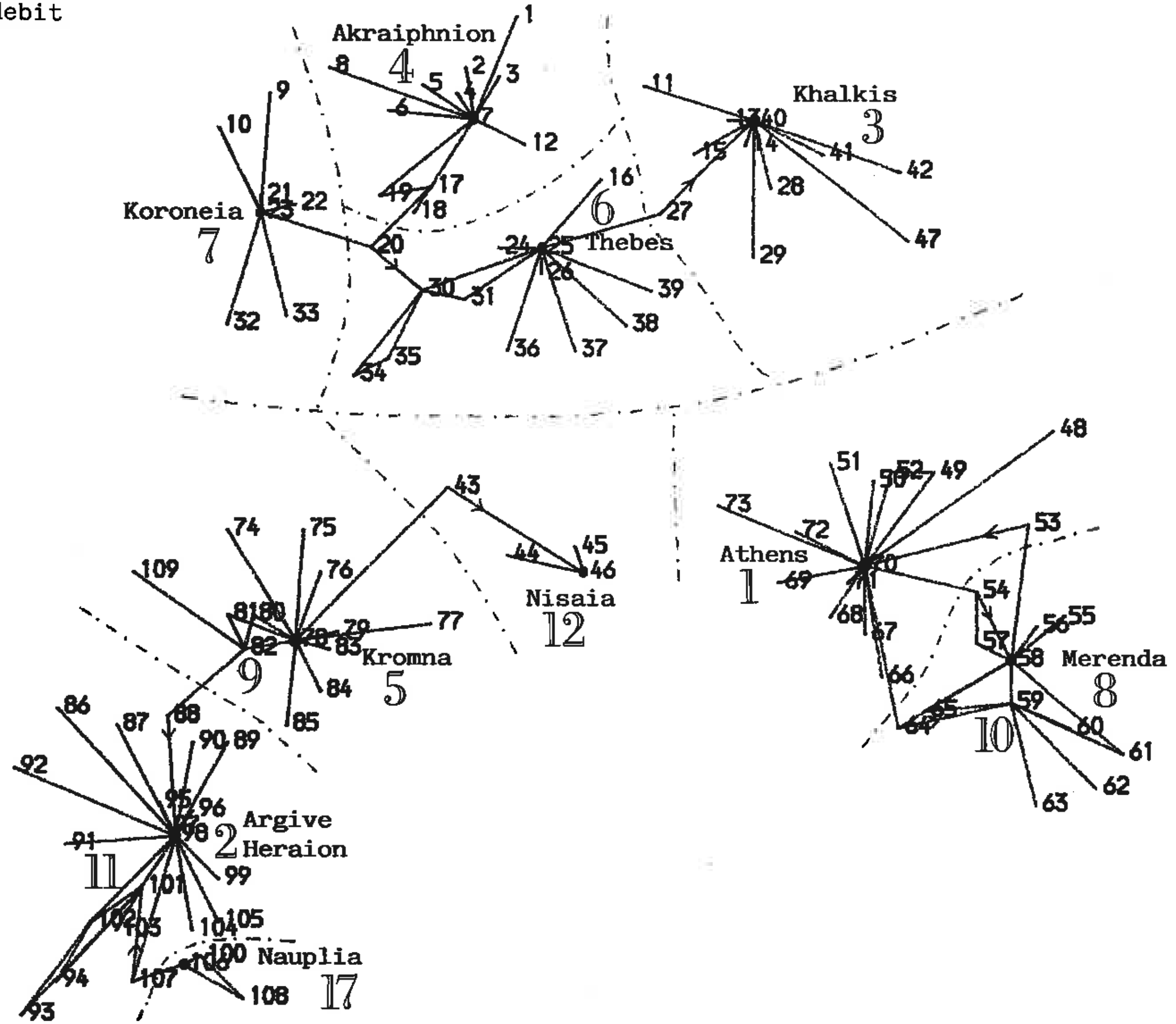


Figure 6: $\alpha = 1.05$

$\beta = 0.175$

$T = 8$

$\geqslant$ 75% max. debit

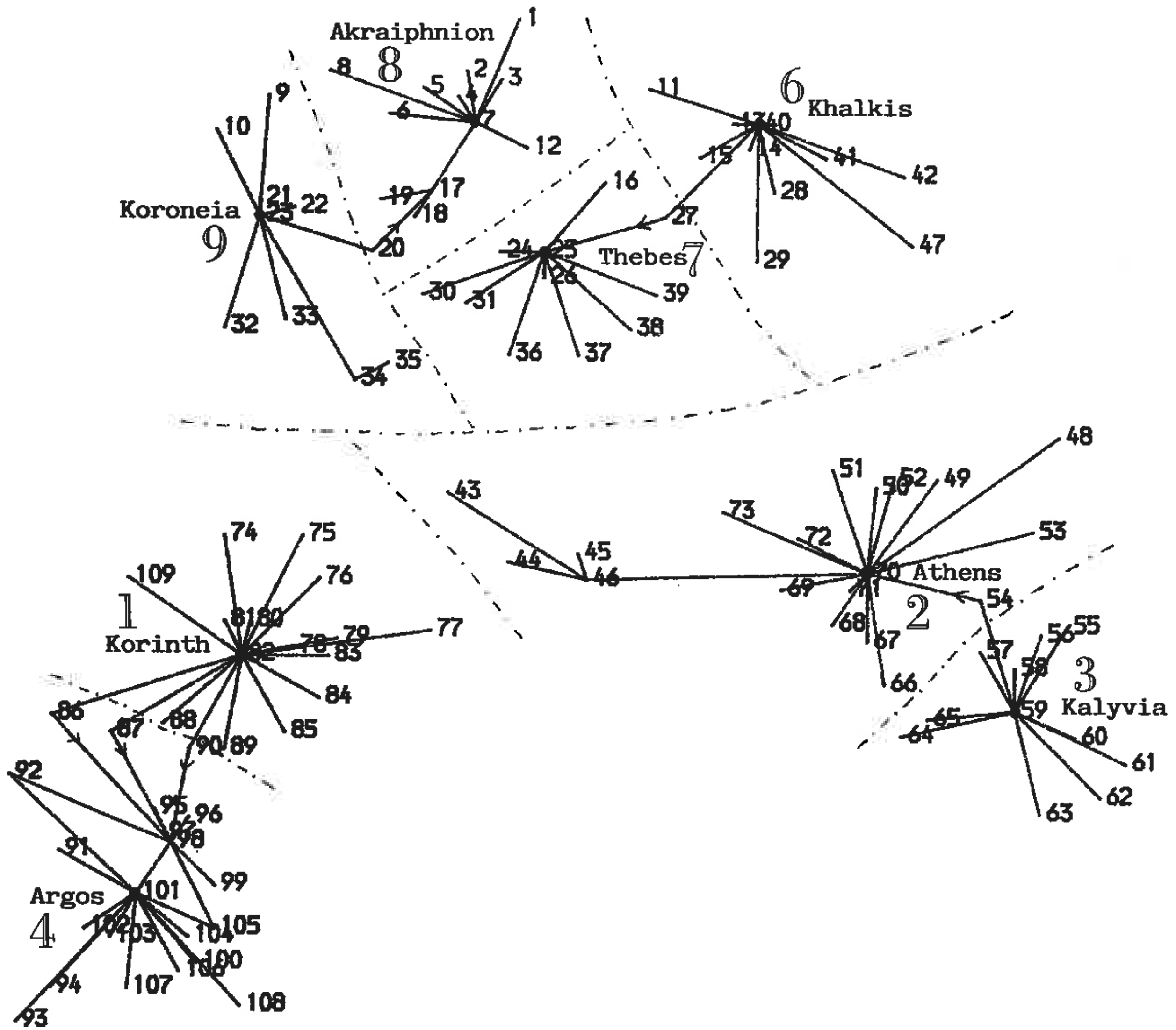
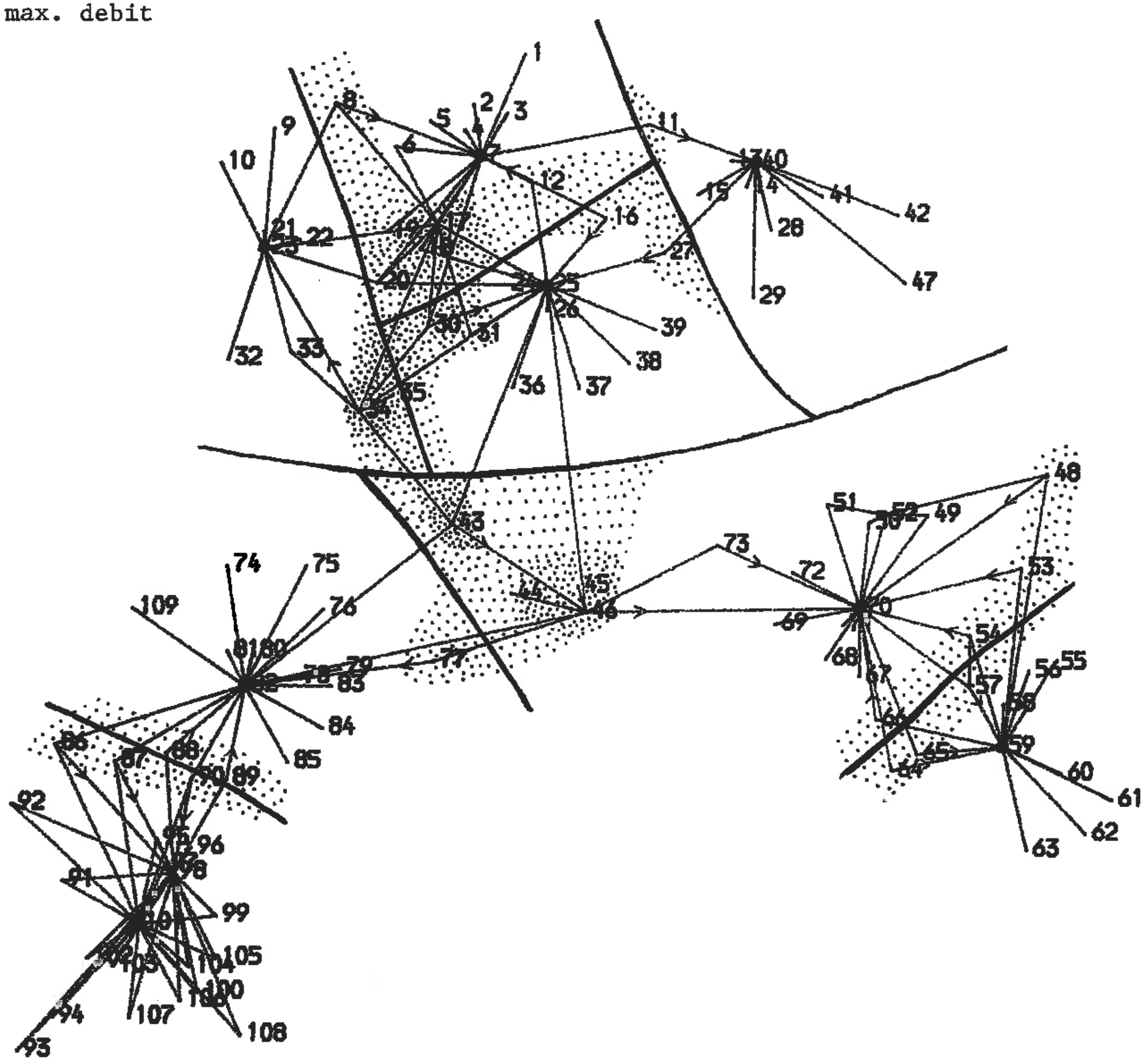


Figure 7: $\alpha = 1.05$

$\beta = 0.175$

$T = 8$

$\geqslant$ 25% max. debit



Mathematical Appendix: spatial interaction and location model

$$I_{ij} = A_i O_j W_j^{\alpha} e^{-\beta c_{ij}} \qquad [1]$$

where

$$A_i = 1/\sum_k W_k^{\alpha} e^{-\beta c_{ik}} \qquad [2]$$

Calculation of $\{W_j\}$: calculate [1] using a set of guessed starting values for W_j (for egalitarian start, set all values equal). Calculate

$$D_j = \sum_i I_{ij} \qquad [3]$$

where D_j is the total credit to j. If $D_j > W_j$, the simulated credit to j is greater than the original guess, and the hypothesis is that W_j should be increased; if $D_j < W_j$ then it is less than the original guess and should be decreased. At equilibrium, we require

$$D_j = W_j \qquad [4]$$

So, substitute for D_j from [3]

$$\sum_i I_{ij} = W_j \qquad [5]$$

and for I_{ij} from [1] and [2]

$$\sum_i \frac{O_i W_j^{\alpha} e^{-\beta c_{ij}}}{\sum_k W_k^{\alpha} e^{-\beta c_{ik}}} = W_j \qquad [6]$$

These non-linear simultaneous equations can be solved for given values of α and β to give $\{W_j\}$, the spatial pattern of settlement size. For the feedback version, $\{W_j^F\}$, set O_i equal to W_i and rerun.

Notation

I_{ij}	=	interaction from i, the origin zone, to j, the destination zone
O_i	=	the size of i
W_j	=	the resources at (or attractiveness of) j
c_{ij}	=	the distance from i to j
α	=	a parameter reflecting the benefit of concentrated resources
β	=	a parameter reflecting the ease of communications
$e^{-\beta c_{ij}}$	=	a negative exponential function arising from entropy-maximisimg methods and having the same effect as a distance-decay function.