USABILITY OF LARGE SCALE TOPOGRAPHIC DATA FOR URBAN PLANNING AND ENGINEERING APPLICATIONS

Examples of housing studies and DEM generation in Tanzania

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Working Group IC/14

KEY WORDS: Usability, Large Scale Topographic Data, Quality Control, DEM, Housing Studies.

ABSTRACT

The creation of large-scale digital topographic databases of urban areas provides, in theory, a rich source of basic data that could be used in a variety of applications. Urban planners and engineers can use such data for both analytical and management oriented applications. In the developing world, Geographic Information Technology (GIT) is increasingly accessible to mapping agencies and local government agencies, opening possibilities to improve the supply of data for GIT applications in urban management.

The paper describes the application of topographic data for two main applications: the generation of a DEM covering the city of Dar es Salaam and the study of housing density in the city with a particular emphasis on unplanned areas. In the development of both applications considerable difficulties related to data quality have been confronted. Several kinds of errors, most of which stem from the data capture process, are described. Many are not systematic and the variation over the database area ranges between 2% and 30% of affected features for a particular problem. Several strategies have been developed in order to isolate and correct for some of these problems many of which could have been isolated with improved quality control procedures.

Ultimately, a DEM and some useful statistics and maps of housing density have been produced. The reactions to these outputs by local planners and engineers indicate that there is indeed rich potential in such data. However, in order to tap this potential effectively, usability should be considered as a basis for spatial data acquisition.

1 INTRODUCTION

Production lines for basic digital topographic databases are increasingly available in many of the world's poorest developing countries. Often the move from analogue to digital systems is being tied to aid projects with a specific mapping component. Parallel developments within agencies that are traditionally large users of spatial data can also be found. For the development of standalone PC or Desktop GIS applications within the map user community, the availability of digital topographic databases seems to offer considerable potential. GIS applications should, in principal, be able to obtain significant benefits from such databases. Potential benefits exist in reducing time for spatial data capture, creating greater flexibility in the number and type of applications possible and introducing new possibilities for linking of data bases for processing and visualisation.

This paper contends that the ultimate value of any digital topographic database is its *usability*. The adoption of the concept of usability as a means of measuring the value of digital topographic data stresses applications oriented criteria. After developing some thoughts on the criteria that may be used to define usability, recent research to derive valued added products from a large scale (1:2500) digital topographic database of the city of Dar es Salaam, Tanzania, is described. The data used covers the main urban area in 1992, approximately 234 square km. Two applications that have direct relevance to the information needs of urban planners and engineers are presented: 1) creating a DEM from contour and spot height information to be used for studies of surface water drainage etc and 2) deriving information on building density and informal housing. These cases show that there are currently considerable barriers for users to overcome before this data can be effectively utilised.

2 GIT ADOPTION AND DIFFUSION IN DAR ES SALAAM

The adoption of GIT by organisations typically goes through several stages of development, moving gradually from stand-alone applications to more complex, integrated systems (Turkstra, 1998). In Tanzania the adoption of GIT seems also to follow this pattern. It is currently very much in the initial stages, with standalone applications being dominant and each application group being primarily internally oriented. GIT has come to Tanzania in the 1990's through a number of parallel developments within the national mapping agency (Surveys and Mapping Division, SMD) and several organisations with an application or research and education orientation. For this paper the roles of the SMD and the Sustainable Dar es Salaam Project (SDP) are particularly important. The SMD being the official source of topographic data and the latter being a project aimed at improving the local capacity for planning and management of the city.

European consultants prepared digital maps at scale 1:2500 of Tanzania's main cities. The project included capacity development at the SMD. The digital databases were transferred to the SMD in 1994/95. Hardcopy maps were printed for sale to the public, this being the primary objective of the mapping component. Gradually, interest has evolved for purchase of digital data, an increasingly important part of the SMD's activities.

The SDP adopted a desktop GIS with a view to create an Environmental Management Information System in 1995, an activity which has not been fully successful (Masser and Sliuzas, 1999). While the SDP's work with GIS has focussed primarily on the strategic planning level, several working groups have also been working on projects focussed on specific localities, necessitating the use of large-scale maps, leading them to purchase a complete digital topographic database from SMD. To date only very limited use has been made of this data by the SDP, although the research carried out by the ITC and described below clearly illustrates the potential which exists for deriving valuable information on both the natural and the built environment from it.

3 THE CONCEPT OF USABILITY

In the process of the creation of the database insufficient attention was paid to the potential users of the large scale topographic data outside SMD, such as SDP, the City Commission and various agencies responsible for utility networks. This situation was aggravated because of the fact that a large part of the production work was done by consultants, with little local knowledge and used to different mapping standards. The rich potential of the digital data has not been easy to realise, also because the data were not captured with GIS in mind, but as mapping data.

The lack of attention to user requirements in mapping organisations is not uncommon, also in a European context. Only fairly recently national mapping agencies have begun to incorporate user requirement studies in their map making procedures. The Ordnance Survey (OS) in the United Kingdom for example has, on the basis of the recommendations in the Chorley report, (Chorley et. al. 1987), started to adopt a positive approach towards the marketing of data and the coordination with and awareness raising of users. The OS has now directed its overall policies at making digital material available to the user in a timely, consistent, convenient and affordable manner (Ordnance Survey, 1999). Also in the Netherlands several projects are ongoing under the umbrella of the RAVI foundation to structure and standardise geographical base data in such a way that it can immediately be used by a variety of end users. Notwithstanding the above, the large scale topodata is currently usually still backdrop data only and not directly suited for GIS analysis using topology, even though identifiers for key spatial features may be available in the database. Adapting the large scale topographic data in such a way that an underlying GIS data model is able to handle the topological relations (depending on user requirements) is expensive. However, the realisation that clients may increasingly use digital data for a different purpose than just mapping, prompts data producing agencies to evaluate the introduction of GIS standards.

To describe the concept of usability in the Dar es Salaam situation, we first analyse what we see as the general criteria to define usability for the Dar situation. This is followed by the application oriented criteria for the engineering applications, which are more specific in nature.

3.1 General criteria

Extent of coverage. In focusing on the existing urban areas, a rather limited map extent has been applied. Dar es Salaam is a rapidly growing city (estimated at 7 % population growth per annum); a large proportion of this growth takes places beyond the boundaries of the digital data. The main application of the data for planning purposes (planning and controlling spatial development and the provision of services) is therefore severely restricted. This holds true also for the analysis of flash flooding problems and urban fringe developments. The digital data has therefore little value for several important tasks in the city. A more strategic view would surely have increased the mapping extent.

Completeness of objects/features. The neglect of local knowledge and weaknesses in quality control procedures have led to incompleteness of important spatial objects such as buildings and roads, topographical features such as rivers, ridges and depressions and artificial features such as contours. The usability is thus strongly reduced. These deficiencies mean that the data cannot be wholly relied upon and additional field verification is required.

Reliability and nature of classifications. In the process of classification of objects and topographical features, several interpretation errors were made, caused by insufficient local knowledge and limited field checks. This leaves the individual end-users no other choice than to manually update the classifications themselves. In addition, the variety of classifications that were implemented in the database do not adequately represent the information that planners and engineers are interested in. Increased interaction with the end-users will lead to a more complete and useful classification.

Topology. The use of the data for several GIS purposes is severely restricted in view of the absence of procedures to ensure topology in the spatial database. Examples of problems are disconnected, intersecting or overshooting contours open building polygons and rivers and roads built up of thousands of loose segments. Many parts of the data seem to have been captured in an inconsistent manner. The large and important road and river layers of the database can thus not be used to their full potential. After the development of precise user requirements the topology requirements need to be worked out and implemented.

Spatial precision. Problems occurred in on the borders some of the map sheets with the connection and the positioning of features, however not due to systematic errors in geopositioning but due to the separation of the mapsheets in the data capture process, making it difficult to remedy. In addition several unreliable values were identified in selected elevation features. Data capture procedures should be established with special emphasis on consistency in mapsheet connection.

Consistency – temporal & spatial. The occurrence of errors in the specific topographic features varies over the database. Per map sheet considerable differences can be found, depending on the activities of the various operators in the data capture process. Some errors only manifest themselves in selected map sheets. The impression to a user, working on a particular map sheet which is error free, might be that other parts of the database can be analysed in a similar way. Procedures need to be implemented to ensure that all operators work in a clearly defined consistent manner.

Temporal relevance. A major issue for any fast growing urban area is access to data of a recent date. Currently map production for Dar es Salaam is operating on approximately a 10 year cycle, which is inadequate given the scale of change. Usability depends on the time gap between data acquisition and product delivery. Establishing priorities for different parts of the city and creating new products for the Dar es Salaam market (orthophotos) may well enable many users to extract more benefit from the mapping process.

3.2 Criteria for the usability of a Digital Elevation Model for infrastructure engineering and design.

The DEM for Dar es Salaam was envisaged to be used in the following application areas: routing & design of non rainfed sewerage systems ***(a)***, studies of flash flooding and routing & design of urban drainage systems ***(b)*** and routing & design of roads ***(c)***.

ad a. The usability for sewerage system design and engineering depends primarily on the positional accuracy of the pixels in the DEM, (particularly the vertical accuracy) and the detail in which relevant terrain features such as sinks, depressions and ridges can be identified. The horizontal accuracy of DEM pixels is less relevant in view of the fact that design slopes of sewer systems are usually within the range of 1:100 – 1:1000. The key element however in defining usability is identifying the level of engineering design that is required. The following usability classification is proposed for a separate gravity sewer system (not discharging rainwater, only sewage).

ad b. In the area of urban hydrology the important DEM related applications are: catchment analysis (i) , flow analysis (ii), calculation of time of concentration per catchment (iii), routing (iv) and the calculation of hydraulic and construction parameters (v).

The following suitability criteria are proposed to be applied for the first 3 applications. For these the DEM:
- Needs to be free of sinks and depressions (i, ii, iii)
- Preferably has a vertical accuracy to the order of 25 cm (ii, iii)
- Should have a pixel size depending on the size of the catchment that is being studied. In urban catchments important drainage features may be relatively small, thus a pixel size of below 25 m is advised. (i, ii, iii).

- Should reliably incorporate important terrain features such as rivers, ridges, valleys, any man-made obstacles, and particularly road infrastructure. This means that even though the DEM may be very accurate and reliable, the quality of the elevation data of the other features determines the quality of the analysis. (i, ii, iii)

For the routing analysis (application iv) the criteria indicated in table 1 under Conceptual Design may be applied. For the calculation of hydraulic and construction parameters (application v), the criteria in table 1 for the Conceptual, Detailed and Final Detailed Design may be used.

design stage	**description**	**usability criteria** ↓vertical accuracy[+/-]	other↓
Initial analysis of the possibilities for gravity sewer construction	Investigate the terrain relief in relation to the relevant features of the built environment (roads, buildings etc.) to get an indication of whether gravity sewerage is at all feasible and in what way. This would be just a qualitative assessment that can be done with visualising some DEM by-products such as a slope map.	1 m	Important terrain features need to be identifiable with sufficient detail to make a go/no go decision. A resolution of 25 m is sufficient. The direction of slopes needs to be identifiable .
Routing and conceptual design	At the conceptual design level, the objective is to provide routes and a basic spatial layout of the primary sewerage system and assess whether the terrain is conducive (hydraulically) for sewerage construction according to engineering standards. The resulting network dimensions and slopes can than be transferred to other software to carry out hydraulic calculations.	50 cm	A resolution of 5 m is sufficient, however resolutions of 1-2 m give better insight in detailed terrain elevation and can be used in conceptual cut and fill calculations.
Detailed design	At the detailed design level, incorporating secondary systems, the accuracy requirements are much higher in order to generate sufficiently reliable data for the hydraulic calculations, maintain minimal cover and reduce excess excavation.	10 cm	A resolution <1 m is required.
Final detailed design and construction	In the final detailed design high accuracies need to be achieved at the network nodes in order to ensure that all elements of the system are constructed according to their design slopes to fulfil the hydraulic system objectives.	1 cm	Current remotely sensed methods do not achieve such accuracy. Additional surveying at network nodes and longitudinal sections is necessary.

Table 1. Usability classification of a DEM to be used for design of gravity sewer systems.

ad c. To express the usability of the DEM for road system design and engineering we distinguish between a separate road (case i) and a road acting as surface drain. (case ii). In case (i) the vertical accuracies in the various design phases are less strict, as they will not have an impact on the functioning of the road system but on the accuracy of engineering cost estimates of cut and fill. It is therefore relatively flexible for all design phases. The values in table 1 may be interpreted as lower limits for Conceptual and Detailed Design. A common option in road design is to use the actual road profile for surface drainage purposes (case ii). In such case, or when the road infrastructure to be constructed potentially interferes with established drainage patterns, the hydraulic characteristics require similar usability criteria in the various design phases as indicated in table 1, to prevent reduced capacities or overflow. In the case of most of the areas in Dar es Salaam however, this design option is not very appropriate, the use of collector drains is more suitable.

4 SPATIAL DATA REQUIREMENTS FOR URBAN PLANNING & MANAGEMENT IN DAR ES SALAAM

The spatial data problems for urban planning and management in Dar es Salaam is compounded by rapid urbanisation, a high degree of informality and human, technical and financial resource constraints. Population growth rates for Dar es Salaam are, for example, believed to be about 7% per annum and as much as 70% of the population is being housed in so-called informal settlements (Sawio, 1998). Given that large scale maps covering the major part of the urban area are being produced with approximately a ten year interval, in 1982 (machine plots only) and again in 1992 (digital coverage), little was actually known about the full extent and density of the urban development.* With much of the data which western planners take for granted being simply not regularly available, planners in Dar es Salaam must often rely on professional judgement and sampling to establish basic indicators describing the *state of city*. The paucity of data available for policy making and planning requires that investments in any data acquisition, including spatial data should explicitly consider user requirements and usability issues.

5 THE TEST APPLICATIONS AND RESEARCH APPROACH

The extent and growth of informal settlements and the lack of infrastructure are two of the 8 main thrust areas tackled by the SDP and the local government in Dar es Salaam. Our objective was to establish the feasibility of deriving

* A budget proposal for new aerial photographs to be made in 2000 has been pushed back until at least 2001.

information on informal housing and the physical terrain (DEM) from the digital topographic data which would benefit local planning and engineering initiatives. The housing information should provide information on the extent and density of informal settlements in 1992 and establish a methodology that would enable similar information to be extracted from future data for analysis of informal expansion and consolidation processes. The DEM on the other hand would provide information useful for engineering studies and could also assist in improving the delineation of particularly hazardous, flood-prone areas.

5.1 Building a DEM

In the development of infrastructure for informal settlements, important cost savings can be achieved if relevant information is available. The potential of city wide digital data on important features such as the terrain and buildings could be instrumental in the development of these plans through GIS and the support to local community initiatives to improve infrastructure services. The product that has been selected in this research is the DEM, the potential use of which has been explained in section 3.2.

The following methodology was used in the DEM generation. A test area, the size of one quarter of a map sheet was identified. The various features in the data set with elevation information were examined visually, and so was the DEM generated through contour interpolation. This procedure was repeated for an additional small area. In addition all contours and other features were examined over the whole area and a DEM with a 10 m resolution was made for the total mapped area. This resulted in the identification of significant problems listed below.

The original database comprises of several layers in a DXF format containing elevation values extracted from aerial photographs through photogrammetric operations. These values are derived for all features in all classes. The features that were used are listed below:

1. Contours in a 2 m interval layer and a 10 m interval layer
2. Spot heights at 6700 locations
3. Roads and footpaths. Elevation information was available for the beginning and end node of segments, 522070 elevation points were extracted from this information.
4. A layer with rivers and water bodies, also for the beginning and end node of segments, 113724 elevation points were extracted.

The following problems appeared in the database during the process of DEM generation:

Incorrect labels. In many map sheets incorrect elevation value labels appeared on all features. This was particularly the case for the contour labels where groups of contours in all map sheets would contain different elevation values in contiguous segments. Usually these values were 0, but also other values occurred. The errors were traced through visual inspection of a selected contour with a particular value that was checked for any gaps associated with a contour from the total set. This proved to be a good procedure except for the areas where gasp in contours occurred due to other reasons (see below). The spot heights, whether they were extracted from the spot height set or from the roads and rivers set, contained many zero values occurring particularly in the northern part of the area. These were eliminated. The relative difference between all other points and a DEM based only on the corrected contours was analysed with a conventional ground survey control point set. Those points that belonged to the 5% most deviating were eliminated.

Gaps in contours. Upon overlaying of the building data, it was concluded that these gaps only occurred at locations of buildings and on only a limited number of map sheets in the range 10–28 m. above M.S.L. The remedy that was attempted was to automatically connect the end nodes of broken segments linearly. This was abandoned in view of the error introduced and the little effect that the gaps have on the interpolation result in view of their short length.

Shooting contours. At some locations a bundle of contours would shoot out over a large distance, apparently due to a digitising error, causing a sudden rise or fall in the terrain. Most of these locations were identified through the production of a gradient map. The shooting segments were manually corrected.

Crossing contours. In a number of map sheets, intersecting contour lines were identified. These were detected automatically for each particular value contour by identifying non-redundant nodes. The correction was done manually.

Density of spot heights. The distribution of elevation points in the spot height set is irregular over the area. The interpolations from contour lines and spot height data yielded insufficient detail in flatter areas, which is why the additional elevation data was extracted from the roads and rivers layers, resulting in a very high density of elevation information (see table 2).

Map sheet consistency. Not all map sheets connected without problems. The incorrect connections were attempted identified by selecting per single value contours and checking the number of segments. This proved to work well except for those parts of the database where frequent gaps in contours existed.

The whole process of improving the data to generate the DEM was very time consuming. Quality control during the handling of the above mentioned problems was extremely important, after each step had been completed, to ensure that the problem was indeed removed. In total various people spent some 4 months in the DEM generation. The spatial precision of the final DEM after completion was tested with the use of a control data point set. The result of this test is briefly presented below, for further information refer to (Sliuzas et.al. 1999).

No. of control points	62	Process
St. deviation (m)	0.867	The contour map was combined with the spots, roads and river maps, where preference was given in this order. The final map used in the interpolation process contained 743318 elevation pixels, after elimination of 71500 elevation pixels that overlapped. This indicates that a very high 31.9 % of all pixels in the total Dar es Salaam area contained elevation values.
Average difference (m) [(1)]	0.703	
Median difference (m)	-0.095	
Minimum difference (m)	-1.67	
Maximum difference (m)	2.18	
Pixel size (m)	10	

Table 2. Spatial precision of final DEM

The accuracy is expressed as the difference of the elevation in the DEM and that of the control point.
[1] Based on the average of all absolute values of differences between control points and DEM.

Compared with the usability criteria identified earlier, it is concluded that the derived DEM is probably useful in conceptual design of roads, sewerage and drainage systems, but certainly not in detailed design.

5.2 Deriving data for the analysis of informal settlements

A recent study of land management practice in Tanzania, concluded that the limited public resources available should be deployed strategically in order to assist local communities with their efforts toward social formalisation (Kombe and Kreibich, 1998). The paucity of data on informal settlements is however a major barrier to the development of a rational strategy for prioritising and selecting appropriate areas for intervention. One possible solution to the data problem would be to convert the digital topographic data from the mapping environment into a GIS environment that would enable polygon generation, classification and analysis. This would provide a useful baseline for future work on settlement development in the city and consideration of possible strategy adjustments.

The original database consists of 3 identifiable layers related to buildings (public buildings, other buildings, and under construction). To facilitate processing the city was divided into 6 zones, which contained between 9,400 and 106,800 buildings each. In total approximately 230,000 building polygons were generated. Although conceptually straightforward the processing proved to require a considerable investment in time to implement. Quality control after each step being extremely important to safeguard against unwanted effects or incomplete operations. The process of testing a method and its implementation, including the delineation of housing areas, required in total in the order of 3 person-months to complete. Many difficulties could be attributed to deficiencies in the data capture procedures. Common errors were: 1) features wrongly coded as buildings; 2) buildings wrongly classified; 3) missing buildings, including at least one public building (school) with a size in excess of 200 square metres; 4) incomplete polygons, especially prevalent along the map tile boundaries; and 5) numerous cases of multiple data capture (i.e. double digitising).

Several more fundamental issues were also evident. Firstly, the apparent lack of familiarity by the photogrammetric operators of the concept of a “swahili house”(see Figure 1.a.). This house type is particularly common in Dar es Salaam and is found in both formal and informal housing areas. The types of situations commonly found in dense informal areas is shown in Figure 1.b with its cartographic representation in Figure 1.c. Failure to recognise such model houses has lead to considerable errors in building delineation and unnecessary and misleading amalgamations of closely spaced, but separate buildings. This situation reduces the usability of the data for house counts and studies of building sizes. Given the incremental nature of housing construction in informal areas, more reliable data may have served very usefully in longitudinal housing studies.

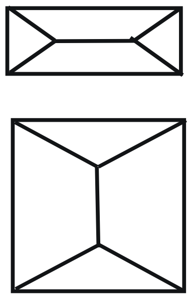

Figure 1.a: standard Swahili house consis-ting of a 2 buildings (8x12m and 3x8m).

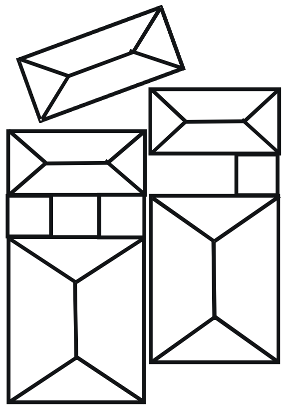

Figure 1.b. some variations on the standard house showing a cluster of modified Swahili houses and one small house.

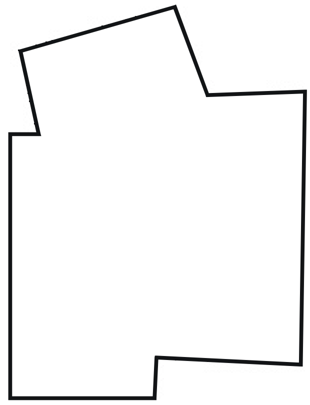

Figure 1.c.: Possible highly generalised representation in database.

Secondly, unsystematic variations in interpretation, delineation and classification are evident throughout the data. Although not confirmed, these errors are likely to be attributable to variations between individual operators, as differences are often discernible between adjoining map sheets. Similar disparities have also been found for the terrain elevation data used to make the DEM. The relatively small photo-scale and the highly complex and dense developments in many areas (see Figures 2.) may have influenced many problems.

Figure 2. Left: exert of 1992 aerial photograph (Original scale 1:12500). Note the high density, irregular distribution of buildings and the highly generalised building forms. Right: exert of building polygon coverage after processing.

Finally, the extent of mapping was restricted to the area covered by the previous 1982 maps. This is a serious disadvantage to many urban management applications that are targeting the recently established settlements in the urban-rural fringe. A recent study with SPOT and ERS data has shown that considerable expansion has taken place in the period 1992-1998 (Sliuzas et al, 2000; Dekker, 2000). The lack of large scale mapping in the fringe is an obstacle to proper monitoring and the development of guided land development strategies for which such base maps could be extremely useful.

Despite the shortcomings inherent in this data it has been possible to generate the envisaged products. Maps and statistics of density for those informal areas included in the photosurvey are now available. The added value for such data is now even more apparent as it will also be used in conjunction with density data derived from SPOT imagery. Tests will be made to use the building centroid data in an attempt to calibrate a classification of urban density (for more information see, Sliuzas et al, 2000).

6 IMPLICATIONS OF FINDINGS FOR SMD AND POTENTIAL USERS

SMD's digital topographic data can be extremely useful for a wide range of urban management applications but usability is extremely dependent upon the particular usability criteria that each application requires in combination with attention for the 7 criteria described above. For the users there are no barriers to using topographic data as a basemap for adding other thematic information but at this time applications with the data itself require substantial investments in quality control and error identification and corrections.

7 CONCLUSIONS

There is a growing need for a regular consultation between suppliers and users of digital topographic data on needs and standards for quality and data sharing. The implications of the use of GIS by an increasing number of users for product definitions and delivery should be considered. It should be pointed out that at present SMD is very much concerned with improving the range and quality of its services to its customers. An increasing number of both local and international customers require digital data services. SMD is one of the many agencies currently co-operating to define new standards for data capture, provision and pricing.

SMD is recommended to improve the quality control over the production process (especially between tiles and operators) and ensure that operators have the required local knowledge to ensure proper interpretation and delineation.

In comparing the quality of the DEM with the usability criteria it can be concluded that the DEM may only be used for initial analysis and conceptual design of infrastructure.

From the housing analysis, useful baseline data has been created from the more established sections of the city, which can be used in conjunction with future data when available.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support and assistance of the Surveys and Mapping Division, Dar es Salaam for allowing us to use this data for our research. This work would not have been possible without the efforts of Ralf Daub, Gaster Kawuubye, Chu Tuan Tu, Misja Visser and our colleague, Frans van den Bosch.

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