A Bibliography of Geomorphometry, the Quantitative Representation of Topography—Supplement 2.0

By RICHARD J. PIKE

Provides over 800 additions and corrections to the 1993 Bibliography of Geomorphometry and its 1995 Supplement 1.0, with a brief update on recent advances

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A Bibliography of Geomorphometry, the Quantitative Representation of Topography—Supplement 2.0

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Abstract This report adds more than 800 references on the numerical characterization of topography (geomorphometry) to a 1993 review of the literature and its 1995 supplement. Several corrections are included. The report also briefly reviews four recent advances and related topics: fractal modeling of fluvial networks, new sources of digital data (emphasizing Internet access), industrial micro-surface metrology, and morphometry in Japan.

The rapid growth of terrain quantification continues through its many applications in geomorphology, hydrology, geohazards mapping, and land-use evaluation. Geomorphometry (or simply morphometry) is an amalgam of Earth science, mathematics, engineering, and computer science; it is known variously as terrain modeling, terrain analysis, and quantitative geomorphology. The discipline has been revolutionized by the computer manipulation of square-grid arrays of terrain heights, or digital elevation models (DEM's), to quantify and portray ground-surface form over large areas. Morphometric procedures are now implemented routinely by programmed algorithms in geographic information systems (GIS).

This is the second update of a bibliography and introductory essay on geomorphometry (Pike, 1993). The first supplement to the listing and a revised essay appeared two years later (Pike, 1995 and 1995a). This report continues my drawing together the diverse, scattered literature on the subject and making it accessible to the research community as a public service. The need for such an effort remains evident from the accelerating use of DEM's in science and technology. Here I add over 800 items to the 2550 in the earlier two listings. More than a dozen references correct the most serious errors in Pike (1993 and 1995). The new entries include both older works overlooked previously and a good sampling of the voluminous material published since the first supplement, which was current through mid-1994. Coverage is inclusive, but not exhaustive.

The appended listing is alphabetized and unannotated, following the format of its two predecessors. The 60-topic organization of geomorphometry developed initially (Pike, 1993, Table 2) and later revised (Pike, 1995a, Table 2) still accommodates most of the latest entries. The various qualifications and caveats on accuracy and completeness stated earlier apply equally to this second supplement, which is current well into late 1996. Preparations for distributing the original bibliography and subsequent updates on-line over the Internet from a U.S. Geological Survey web site continue. The combined reference file now exceeds 3400 entries (a 0.7-mb digital file). Similarly, plans for sorting the listing topically and chronologically—both highly desirable given its size and complexity—have not yet been finalized (the file is not encoded in EndNote or other bibliographic-database format).

Highlighted here briefly are advances in established areas of morphometric research, emphasizing the now-ubiquitous DEM. On the whole, applications of numerical techniques to landscape modeling—commonly combined with nontopographic data, rather than just accounts of technique development and studies of small-area field problems, are more common now than previously. This trend may reflect a maturing of the discipline into a source of...
reliable tools to solve applied problems of regional scope (for example, computing basin hydrographs and estimating soil erosion and the movement of ground water). Featured in this supplement are four active, albeit not necessarily new, areas that have been identified since the release of Pike (1995) and appear particularly germane to morphometry at this time: fractal representation of channel networks—including developments in self-organized criticality, sources of digital data—emphasizing Internet availability of information, the topography of industrial micro-surfaces, and Japanese work in morphometry.

**Fluvial geomorphology and fractal models**

Analysis and modeling of fluvial systems continue to lead all other new developments in morphometry (Kovar and Nachtnebel, 1996; Burlando and others, 1996). Several areas are active. Among these are the novel adaptation of stream-branching topology to networks of valley glaciers (using a 90-m-resolution DEM; Bahr and Peckham, 1996) and further applications of the popular DEM-based TOPMODEL algorithm for simulating watershed hydrographs (Band and others, 1995; Quinn and others, 1995; Wolock and McCabe, 1995). Various refinements are still improving the fidelity of stream networks and drainage basins extracted from DEM's (Meisels and others, 1995; Bennett and Armstrong, 1996; Brändli, 1996; Garbrecht and Martz, 1996b; Ichoku and others, 1996; Geosoft, 1996). The approaches differ. Pilotti and others (1996), for example, have created new interactive software for the DEM-to-watershed transformation, whereas the RiverTools package developed by Peckham (1995) is fully automated. A cautionary note is emerging amid the euphoria generated by this breakthrough in morphometry (Pike, 1993, Table 3). Emphasis has shifted from simply automating the transformation to assessing accuracy of the results, with respect to both the numbers of extracted drainage cells (Lee and Chu, 1996) and to the uncertainty of the delimited catchment boundaries (Miller and Morrice, 1996). Other diagnostic work has examined the accuracy of basin slope and other catchment parameters derived from DEM's (Kienzle, 1996; Lagacherie and others, 1996). Aside from biases built into specific DEM-to-watershed algorithms, fidelity of the resulting drainage nets, basins, and parameters appears to depend primarily upon accuracy of the input DEM and its grid spacing.

Many researchers have used DEM-derived channel networks to model the spatial topology of drainage systems. Considerable attention is being devoted to understanding the scale-dependency of such networks, notably their self-similarity as expressed by fractal measures (Maritan and others, 1996; Rigon and others, 1996; Sapozhnikov and Fouloula-Georgiou, 1996b). This field is so active that its many findings, some of them contradictory, have yet to be resolved. Nikora and others (1996) reviewed the prevailing conclusions on fractal structure of channels and their networks and found "no common point of view" among the various investigators. This lack of agreement extends to such recent developments as the applicability of self-organized criticality as well as to the validity of fractality itself.

Recent DEM-based work on the spatial organization of river networks has linked their observed fractal structures with models of self-organization (Phillips, 1995b). "River patterns show consistently fractal and multifractal characteristics through experimental analysis of digital elevation maps" (Rinaldo and others, 1993). This recognition of self-organization in stream patterns has led some authors to ascribe the spatial orderliness to self-organized criticality, a generalizing concept adapted from physics that may have great interpretive capability (Takayasu and Inaoka, 1992; Murray and Paola, 1996; Bak, 1996; Hergarten and Neugebauer, 1996). Very briefly, self-organized criticality is a dynamical state linked to principles of energy dissipation (Bak and others, 1988; Phillips, 1995b). It is characterized by fractal
(power-law) scaling in space and time, related to the occurrence of spatiotemporal chaos and intermittency in the operation of (here, land-shaping) processes (Staum, 1996, p. 1711-1712; Sapozhnikov and Foufoula-Georgiou, 1996a, p. 1109-1110). The explanatory power ascribed to self-organized criticality in geomorphology is being challenged. While accepting the self-affinity and self-organization of many fluvial systems (Sapozhnikov and Foufoula-Georgiou, 1996b), these two authors (1996a) argue that current models of river networks and landscape evolution do not exhibit the necessary critical states. Sapozhnikov and Foufoula-Georgiou (1996a) also raise concerns over problems of inference that may arise in testing hypotheses about the multi-fractal character of topography by resorting to computer-simulated, rather than field- or map-derived, landscapes. Without tests based on empirical, morphometric observations, perhaps all that can be concluded thus far of this new development is that "while ... geomorphic evolution can be self-organizing, it would not be accurate to say it is self-organizing" (Phillips, 1995b).

A reaction to earlier enthusiasm over the putative fractality, or self-similarity over many scales, of topography is emerging in the morphometric literature. It is important, first, to distinguish the two contrasting modes of topographic characterization now prevalent in fractal studies: that of planform pattern \((X,Y)\), typically of stream channels, just discussed above (for example, Claps and Oliveto, 1996) and that of the distribution of continuous elevation, or relief \((Z)\) (for example, Outcalt and others, 1994). The two describe quite different attributes of topography. (I have yet to see a properly controlled experiment comparing values of the fractal dimension \(D\) computed in each mode for the same piece of terrain.) Although certain spatial attributes of fluvial networks \((X,Y)\) appear to be fractal, other attributes of terrain \((Z)\) do not. Evans and McClean (1995) contend that continuous land-surface relief is not unifractal (monofractal), and may be at most multifractal, while Andrle (1996a, b) finds that even the west coast of Great Britain, widely regarded as one of the classic examples of a fractal planform, is not statistically self-similar over its measured scale range. Rouvray (1996) offers a more general critique from several points of view, stating of computer-drawn fractal landscapes (see also, Evans and McClean, 1995) that "The initial impression of realism is soon followed by the realization that this is an entirely artificial construct." Such recent qualifications of the sweeping claims initially made for the intrinsic fractality of the ground surface mark a healthy step toward a more measured incorporation of the fractal concept into morphometry, geomorphology, and geography.

Access to data and other information

Morphometry has been moving into cyberspace, which offers free or low-cost access to data, software, and references. Digital elevation models and digital line graphs can now be downloaded over the Internet. Providers of digital data in the United States include the Geological Survey (USGS, 1994) at [http://www.nsdi.usgs.gov/nsdi/wais/water/gcip.html], the National Imagery and Mapping Agency (NIMA, formerly the Defense Mapping Agency, DMA) at [http://www.nima.mil], as well as commercial firms (Golden Software, 1995; Micropath, 1995b). This trend is nicely exemplified by the recently declassified Geosat data for Earth's seafloor, available at no cost at [http://www.ngdc.noaa.gov/mgg/announcements/announce_predict.html] (Carlowicz, 1995) or at [http://topex.ucsd.edu] (Smith and Sandwell, 1996). Also, the entire Digital Chart of the World (DCW) can now be downloaded at [http://waisqvarsa.er.usgs.gov/public/dcwindex.html]. Bruce Gittings (1996) has been maintaining a master list of available digital elevation data sets at [http://www.geo.ed.ac.uk/geoinfo/dem.sen d] (or contact him at the University of Edinburgh at <bruce@geo.ed.ac.uk>). Bresnahan (1995) provides a shorter list of on-line sites for accessing elevation data. Unclassified developments at NIMA may be followed in MAPLINES, a newsletter from...

Software for morphometric analysis, typically in DOS, WINDOWS, and UNIX environments, is available over the Internet, free (Guth, 1995; Wessel and Smith, 1995) as well as for sale (Golden Software, 1995; at <http://ra.nilenet.eom/~theprofsoftwright/s urfer.html>) or by license (Rüdiger Köthe's program "SARA" for automatic relief analysis is now available; contact him at <koethe@uggg01.dnet.gwdg.de>). Peckham's (1995) "RiverTools" software for fluvial networks is available at <http://cires.people/peckham.scott/RT.html>. A demonstration of results from GRASS software modules for terrain analysis and erosion modeling may be seen at <http://www.brad.ac.uk/cc/documentation/ grass/viz/erosion.html>. Few bibliographies of morphometric work are online at this time. A listing of over 350 entries, "DTM's, Relief Analysis, Relief and Soils, and Relief and Hydrology", by Rüdiger Köthe (University of Göttingen, Germany) is available at <http://uggg-pc-s1.uni- geog.gwdg.de/pg/sara/litdgm-e.htm>. Köthe's compilation, little of which has been incorporated into this report, contains recent European work on morphometry that is largely unavailable in North America.

The digital terrain data so essential to morphometry, and the analytic or mapping software to manipulate them, have been sold for some time on media other than the Internet, commonly CD-ROM. Among these is Clark University's well-known GIS package IDRISI (Eastman, 1992). Recent additions include Chalk Butte (1995), Florinsky and others, (1995), Micropath (1995a), Natural Systems (1995), Row and Hastings (1994), Russ (1994), the U.S. National Geophysical Data Center (1995 and 1996), and Geosoft (1996). Other data sets and software packages are advertised in scientific, technical, and trade publications. Much general statistics and mathematics software for matrix data can be readily adapted to analyze digital elevation models.

Advances in data compilation continue to improve the quality and quantity of DEM's available for morphometry. The U.S. National Geophysical Data Center (NGDC) has released gridded elevations from the Global Land One-Kilometer Base Elevation (GLOBE) Project for 60% of Earth's land surface (NGDC, 1996). This hybrid data set, compiled from existing information, is projected to be 100% complete in 1997. Similarly, NIMA has released its Digital Terrain Elevation Data (DTED) Level 0 (30 arc-seconds, nominally one-kilometer, posting) for the World (information at <http://164.214.2.59/geospatial/products/DT ED/dted.html>). Coverage of this data set, also a hybrid compiled from varied sources, some of them outside the U.S., was still less than 100% as of late 1996 but is expected to be complete by early 1997, when a CD-ROM is scheduled for public availability. This is a thinned data set from NIMA's Level 1 (15 arc-seconds) holdings. A 9-arc-second (about 250 m) DEM, termed the "Geodata 9-second DEM", has just been released for the entire Australian continent (Australian Geological Survey Organization, 1996). Available in 37 tiles or blocks at 1:1,000,000-scale, and in various formats, the DEM is derived from contour-map data believed accurate to better than 10 m. DEM's derived from 1:50,000-scale maps are obtainable, albeit at substantial cost, for all of Great Britain (Ordnance Survey, 1995). The French DEM data are also expensive. These and many other data sets are described in Gittings (1996).

However welcome these new DEM's, such compilations from existing sources must be regarded as only interim data sets. It is the Global Positioning System (GPS) and synthetic aperture radar interferometry (InSAR) that seem to hold the greatest promise for fine-scale regional data on ground-surface form. GPS has revolutionized geodesy—accuracy of heights measured from GPS is now down in the centimeter range (Wu and Lin, 1995), but its future as a direct DEM provider remains unsure. Because economically measuring the large number of GPS heights required for a DEM still poses a problem (Jeyapalan, 1995), morphometric applications of GPS are virtually nil at this time. Only small areas have been contoured at high accuracy from

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GPS elevations (Fix and Burt, 1995). Still, current topographic uses of GPS, mainly improved control for new photogrammetric work (Greening and others, 1994) and precise leveling of existing DEM's, are important advances. Synthetic aperture radar Interferometry (variously InSAR or IFSAR) appears to have greater immediate potential for DEM creation. No fewer than five InSAR missions for DEM generation were under consideration in the United States as of late 1996 (William Acevedo, USGS, personal communication, 1996). While not as new or as accurate a technique as GPS, InSAR derives particular importance from its projected deployment on the Shuttle Radar Topography Mission (SRTM), a joint NASA/DOD plan to map the World's topography in the year 2000. Modified SIR-C hardware will be flown to image 80% of the land surface between 60 degrees north and 56 degrees south latitude. From these data a global DEM, at an anticipated spatial resolution of as little as 3 m locally (10 m coverage worldwide), is to be created (Zebker and others, 1994; Meade and Sandwell, 1996). Accordingly, much attention is being given to evaluating and improving the quality of the anticipated InSAR measurements (Mrstik and others, 1996; Pritt, 1996).

The spectacular, and recently declassified, Geosat altimetry (Smith and Sandwell, 1996) and other digital data needed to create regional bathymetric DEM's (Bourillet and others, 1996; Pratson and Haxby, 1996) continue to advance the practice of seafloor morphometry. Recent results include recognition and quantification of systematic errors in the ETOPO-5 depth data (Levitt and Sandwell, 1996; McNutt and others, 1996), geologic and geophysical interpretation of features on the Pacific seafloor (Auzende and Collot, 1996), improved contour maps of the global ocean floor (Sramek and Johnson, 1996), bathymetric-surface modeling using machine-learning techniques (Dysart, 1996), and numerical maps of seafloor classification, including roughness provinces and morphologic units (Herzfeld and Higginson, 1996). The latter work reveals the remarkable, technique-driven progress in the application of quantitative methods to regional seafloor taxonomy over the last quarter-century (compare, for example, Holcombe and Heezen, 1970).

Micro-surface morphometry

Industrial metrology, the roughness quantification of manufactured surfaces, is an important application of morphometric principles not known to most students of the land surface. The 50 publications referenced here only hint at the rapidly expanding literature; for book-length reviews see Russ (1994) and Stout (1994). Some work in quantifying micro-scale surfaces, notably those of fractured and faulted rock faces, is familiar to Earth scientists (Türk and others, 1987; Power and Tullis, 1991; Ameen, 1995; Brown, 1995). However, a wealth of experience in morphometry is available from high-technology manufacturing and materials science. Metrology, also known in industry as "surface topography", is related to general geomorphometry, which treats continuous landscapes that lack well-defined spatial structure (Pike, 1993), although some micro-surfacing processes can create such structure (Amar and Family, 1996). Metrology is highly applied and practical. It arose from the needs of mechanical engineers (together with the advent of the necessary equipment) to quantify surface wear of moving parts, typically metal bearings, and relate surface measurements to the properties of lubricants, the composition of bearing alloys, and methods of surface finish (Thomas and Charlton, 1981). More recently surface measurements have been correlated with processes by which thin films of materials are deposited on smooth substrates, and other applications in materials science (Amar and Family, 1996; Singh and others, 1996). Much of this work appears in Wear, Surface Topography, Industrial Metrology, Precision Engineering, the Journal of Computer-Assisted Microscopy, and other specialized serials. The key role of advanced materials in current manufacturing suggests that metrology will continue to develop fresh descriptive approaches that feed into landsurface morphometry.
Metrology has progressed steadily since World War II, from central-tendency and dispersion descriptions of micro-profiles on metal bearings (Myers, 1962; Thomas, 1981), through the modeling of continuous metal surfaces as random, isotropic Gaussian fields using autocorrelation and spectral analysis (Whitehouse and Phillips, 1978), to a major shift just now underway. This change, the advent of digital 3-D imaging and micro-topographic mapping (Russ, 1994; Stout, 1994) of metal, semiconductor, and even organic surfaces (Mechaber and others, 1996), is revolutionizing metrology. Methodological limitations of the traditional profile sampling by contact and noncontact stylus (El-Soudani, 1978; Nowicki, 1985; Sherrington and Smith, 1987) have been overcome by such precision instruments as the scanning tunneling and atomic force microscopes and optical interferometers (Wickramasinghe, 1989; Robinson and others, 1991). These instruments image and measure industrial surfaces at very fine resolution and enable contour maps to be created down to the atomic scale. With the linear microtopographic profile thus giving way to the continuous surface as the preferred sampling design (Stout, 1994), all the techniques of spatial analysis have become available to micro-morphometry. Recent results by Rosén and others (1996) exemplify the significant improvement in information content of 3-D surface parameters over 2-D measures. The descriptive methods of 3-D analysis in metrology, one of the first disciplines to apply fractal concepts to surfaces (Thomas and Thomas, 1986; Brown and others, 1993; Russ, 1993 and 1994), now rival those of Earth science in their complexity (Dong and others, 1994a, b; Amar and Family, 1996).

**Morphometry in Japan**

Over 70 references, all obtained since Pike (1995), improve access to Japanese work not commonly well-known outside that country. Although some terrain quantification was evident in Japan before World War II (Tada, 1934; Imamura, 1937; and a few other early references in Pike, 1993), the pace has accelerated with recent advances in computers and digital data. A good sampling of older postwar Japanese-language work in morphometry, which explored much the same suite of geomorphic problems addressed elsewhere at the time (Tokunaga, 1966; Hirano and Yokota, 1976; Kohchi, 1981), is included here. Communication of results remains something of a problem, as many Japanese papers still have only an English abstract and figure captions (Iwahashi, 1994; Yoshiyama, 1994; Lu and others, 1995; Takeda, 1995), but the trend in Japan is toward increasing publication in English (Lu and others, 1996). (The trend in the opposite direction is non-existent.) Morphometry in Japan typically is practiced by academic geomorphologists and geographers, as well as by government technicians responsible for quantitative map-based input to land-use policy and public safety. The country is completely covered by several digital data sets, including topography and geology. These data are used for large-area morphometric analyses based on the Japanese national standard DEM at resolutions of 1 km and 250 m, and on samples of the still incomplete 50-m DEM (Gittings, 1996).

Much of the new DEM-based work in Japan is regional slope mapping and hazard evaluation (Akagiri and Momikura, 1985; Kobashi and others, 1985; Kobashi, 1987; Ohmori and Sugai, 1995). These are immediately practical issues in humid and mountainous Japan, where the population is concentrated downstream on alluvial flats flanked by steep slopes. Closely related concerns are Holocene channeling and sedimentation (Oguchi, 1995, 1996). Digital-cartographic problems encountered in the course of manipulating the DEM data are similar to those addressed elsewhere (Shiono and others, 1985; Lu and others, 1989, 1995, 1996). Development of the software needed for morphometric analysis has also progressed, from relatively simple applications (Nogami, 1983) to multi-function packages based on image-processing concepts (Nogami, 1995; Lu and others, 1996). Among the more exciting of the new Japanese results is the three-parameter
morphometric classification of Iwahashi (1994), who used the 1-km DEM to map 16 terrain types across all of Japan. This paper, which is being translated into English, marks a major advance over prior Japanese research in numerical terrain taxonomy (for example, Yoshida and Akojima, 1986). A particularly influential study has been that of Takayasu and Inaoka (1992), who simulated the evolution of eroding stream networks and concluded that their fractal-scaled model showed evidence of self-organized criticality (see, for example, discussions by Phillips, 1995b; Sapozhnikov and Foufoula-Georgiou, 1996a).

Updated work

Advances in the research areas of geomorphometry already identified (Pike, 1993, 1995a) continue unabated. Several of these are discussed above. Briefly, other new developments have occurred in hazards modeling (Jakob and Bovis, 1996; Gao and Lo, 1995), viewshed analysis (Fisher, 1996; Wang and others, 1996), GIS implementation of morphometric analysis (more than a dozen papers in Kovar and Nachtnebel, 1996), evaluation and improvement of DEM quality (Gesch, 1993 and 1994; Giles and Franklin, 1996), the comparative merits of square-grid DEM vs. TIN (triangulated irregular network) data structures (Kumler, 1994), delimitation of ecoregions from DEM's and other map data (Gallant and others, 1995), parsing the fluvial landscape into sub-basin facets (Dymond and Harmsworth, 1994; Dymond and others, 1995), evaluating the relation between topography and properties of vegetative cover (Florinsky and Kuryakova, 1996), creating complex digital images to visualize and interpret geomorphic features (Wester and Lundén, 1996; Shaw and others, 1996), regional meteorology (Briggs and Cogley, 1996; Fu and others, 1995), modeling geomorphic process (Perrin and others, 1993; Prosser and Dietrich, 1995; Schmidt and Montgomery, 1995; Verrecchia, 1996), modeling regional tectonics (Helm, 1995; Kooi and Beaumont, 1996), the interpretation of planetary surfaces (Bridges, 1995; Cabrol and others, 1996), and measurement of Earth's ice surfaces (Bamber, 1994; Jacobsen and Theakstone, 1995; Manninen, 1996). Some of the broader theoretical consequences of this work are developed in Phillips' (1995a) discussion of nonlinear dynamics and the evolution of geomorphic relief.

Finally, two new serials, Fractals (the first volume was issued in 1993) and the International Journal of Shape Modeling (first volume in 1994) provide additional venues for the publication of morphometric research.

Proceedings of the Geomorphometry Symposium at the 1993 meeting of the International Association of Geomorphologists were published as a special issue, Supplementband 101, of the Zeitschrift für Geomorphologie edited by Pike and Dikau (1995). The contents include: Pike on pioneering morphometrist Walter F. Wood; Weibel and Brändli on adaptive methods for refining DEM's; Guth on DEM calculations from a morphometric toolbox for personal computers; Nogami on morphometric measures for DEM's; Chorowicz and others on pattern-recognition of geomorphic features; Argialas on structured-knowledge models of landforms; Dikau and others on the morphometry of New Mexico; Evans and McClean on the non-unifractality of the land surface; Ohmori and Sugai on models analyzing landslides in Japanese mountains; McDermid and Franklin on Remote sensing and morphometric discrimination of slope processes; Band and others on the effect of different terrain representations on watershed processes; Richards and others on static, kinematic and dynamic process-form relations; and Pike on progress, practice and prospect in geomorphometry.

New Entries

Again, I encourage additions and corrections to this bibliography from its users. I am especially interested in morphometric work that is unlikely to be available in the United States, for example, non-English-language publications from central and eastern Europe. My files on French work are also inadequate. I will be
happy to exchange copies of this report and Pike (1993 and 1995) for such papers. To ensure accuracy and reduce ambiguity, please send reprints or photocopies of proposed contributions rather than just the citations, if at all possible. However, I can entertain new entries if just the following information is provided:

1. photocopy of title page, or
   • title of the work, and
   • the name(s) of author(s); surname plus two initials (or, if one given name, then spelled out)
2. year of publication
3. the exact and complete citation of serial or other form of publication (book, conference proceedings, and so forth), including volume number, issue number, and inclusive page numbers. For meetings give location and dates; for books give name of city and publisher
4. for non-English-language publications, an English translation of at least the title.

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