A Digital Global Map of Irrigated Areas*

Petra Döll and Stefan Siebert[1]

Abstract

For the purpose of global modeling of water use and crop production, a digital global map of irrigated areas was developed. The map depicts the percentage of each 0.5° by 0.5° cell that was equipped for irrigation in 1995. It was derived by combining information from large-scale maps with outlines of irrigated areas (one or more countries per map), FAO data on total irrigated area per country in 1995, and national data on total irrigated area per county, drainage basin or federal state. This paper describes the data set, the data and map sources as well as the map generation, and it discusses the uncertainty of the generated map. We plan to improve this map; therefore, comments, information and data that might contribute to this effort are highly welcome.

Keywords : Global map; digital map; irrigated areas.

Résumé

Dans le but de modéliser l'utilisation de l'eau et la production agricole mondiales, une carte géographique numérique des régions irriguées a été mise au point. La carte décrit par cellule de 0.5° sur 0.5° le pourcentage de superficie qui était équipée pour l'irrigation en 1995. Elle a été établie en combinant les informations de cartes géographiques à grande échelle avec les contours des régions irriguées délimitées (un ou plusieurs pays par carte), les données de la FAO sur la surface totale irriguée de chaque pays en 1995 et les données nationales sur les surfaces irriguées totales par département, par état fédéral ou sur les bassins hydrographiques. Cet article décrit le fichier de données, les sources des données et des cartes ainsi que l'élaboration des cartes. Il discute également les incertitudes concernant la carte élaborée qui devrait etre encore améliorée. Les commentaires, les informations et les données pouvant contribuer à cette tâche, sont bienvenus.

Mots clés : Carte mondiale; carte numérique; régions irriguées.

1. Introduction

In many parts of the world, water and food scarcity are expected to restrict human development during the next century. Irrigated agriculture will play an important role in both of these problem fields. Today, an estimated 67% of the global water withdrawal and 87% of the consumptive water use (withdrawal minus return flow) is for irrigation (Shiklomanov, 1997), while, according to FAO, irrigated agriculture produces approximately 40% of the world's food on less than 20% of the total arable land. For assessing the future water and food situation, it is therefore necessary to determine the possible impact of climatic, demographic and socio-economic change on irrigation water use and irrigated crop production. A necessary prerequisite for this is to know 1) the location and 2) the extent of currently irrigated areas.

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* **Une carte numérique mondiale des régions irriguées**

1 Dr. Petra Döll and Stefan Siebert, Center for Environmental Systems Research, University of Kassel, D-34109 Kassel, Germany. E-mail : doell@usf.uni-kassel.de

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According to FAO, there is irrigation in 174 out of 225 countries world-wide. FAO provides data on the total irrigated area within each country (in their databases AQUASTAT and FAOSTAT), but does not give information on the location of the irrigated areas within the country. The location of irrigated areas is provided by large-scale irrigation maps (e.g. in Achtnich, 1980), which, for one or more countries per map, show the outlines of areas in which irrigation is wide-spread. Adding up all these areas within a country, however, would lead to a gross overestimation of the irrigated area because only a fraction of such relatively large "irrigated areas" is actually equipped for irrigation. Therefore, in order to obtain a map of irrigated areas that is appropriate for quantitative assessments and modeling, the information on the (approximate) location of irrigated areas must be linked with additional information on the total irrigated area within a spatial unit, e.g. a country or a drainage basin.

To our knowledge, we have generated the first digital global map of irrigated areas that shows the spatial distribution of irrigated areas within the countries. This required us to combine heterogeneous information from national and international sources.

Using our water availability and water use model WaterGAP, the map of irrigated areas will be applied to simulate irrigation water use on the global scale (with a spatial resolution of 0.5° by 0.5°). This will help to identify river basin which suffer from water scarcity. In particular, we want to assess how irrigation water requirements will be affected by climate change. Furthermore, based on the 1995 map, scenarios of the future extension of irrigated areas and the corresponding change in irrigation water use will be computed by combining modeling results of irrigation requirements and water availability. In addition, the map will serve as a basis for modeling irrigated crop production. Finally, researchers studying the relation between irrigation and population density and economic development as well as those dealing with wetland protection, the global carbon cycle or global landcover modeling have already indicated their interest in the global map of irrigated areas.

This paper presents a concise description of the data set. It provides information on the data sources, informs on the map generation, and discusses the uncertainties of the data set.

2. Description of the Data Set and its Sources

The digital global map of irrigated areas (Figure 1) is a raster map with a resolution of 0.5° by 0.5° (raster cell area approx. 3000 km² at the equator, and 2100 km² around 45° latitude). For the whole land area of the globe (except Antarctica), the data set provides the irrigation density in 1995, i.e. the percentage of each 0.5 ° by 0.5 ° cell area that was equipped for controlled irrigation around the year 1995. For many countries, no data on the total irrigated area exactly in the year 1995 are available, but for years between 1990 and 1995, and no correction was applied to these data. The definition of controlled irrigation as used by FAO is followed (FAO, 1995). Flood recession cropping areas and cultivated wetlands are not included in the map. In the context of the map, "area equipped for irrigation" is abbreviated by "irrigated area".

The global irrigated area on the map is 2,549,093 km². Of the total irrigated area, 68% is located in Asia, 16% in America, 10% in Europe, 5% in Africa and 1% in Australia. The area actually irrigated in 1995 was smaller than the area equipped for irrigation, but

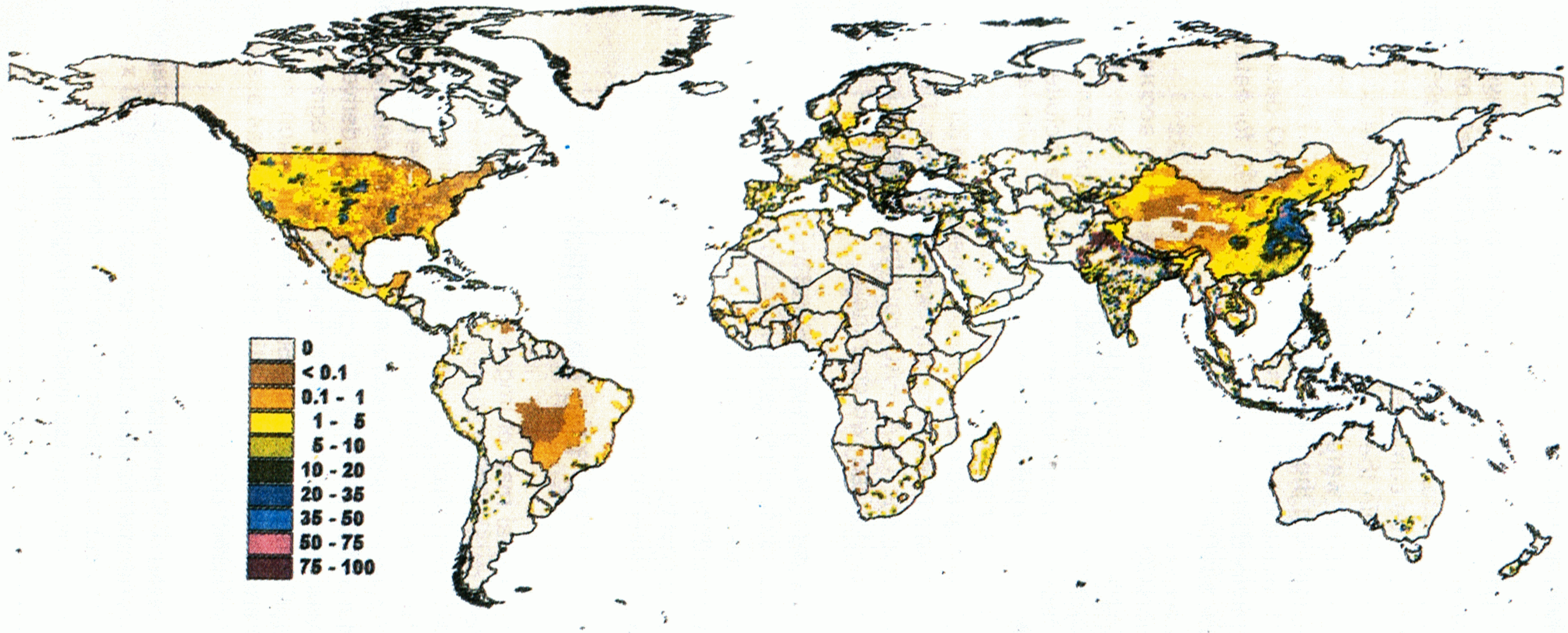

Figure 1. Digital global map of irrigated areas showing the fraction of each 0.5° x 0.5° cell area that was equipped for irrigation in 1995 (in percent)

is unknown for most countries. The data set, together with an extensive documentation (Döll and Siebert, 1999), is available from the authors.

The global map of irrigated areas is mainly based on maps showing the outlines of the main irrigation areas within a country as well as FAO data on the total area in a country that was equipped for controlled irrigation around 1995 (Figure 2). Both types of information had to be combined because maps do not provide information on the irrigation density within the irrigation areas. For most countries, the maps provided by Achtnich (1980) were used. With respect to the total irrigated area within a country, values from the FAO database AQUASTAT (FAO, 1995, 1997a, 1997b) were used if available; otherwise those of the FAO database FAOSTAT (http://www.fao.org) were taken (see Döll and Siebert, 1999, for detailed information on the map and data source for each country).

For 11 countries, more detailed information was taken into account (Table 1). For six out of the 10 countries with the largest irrigated areas (totaling 66% of the global irrigated area), information on irrigated area within subnational units (counties, drainage basins or federal states) was accessible. These include India, China and the USA, the three most important irrigating countries, with 47% of the global irrigated area. For India, a national map of irrigated areas and data of the total irrigated area in each federal state could be obtained, while for China and the USA, values of the irrigated area in each county were available. Due to this detailed information for China and the USA, FAO country values of irrigated area were disregarded in the case of these two countries.

Table 2 shows which fraction of the global irrigated area drawn on the map is based on which type of information. 44% of the global irrigated area was assigned based on an irrigation map plus the value of the irrigated area of the specific country, while 27% was based on county data and 25% on an irrigation map plus the value of the irrigated area in the federal states of a country. Figure 2 provides a map representation of the type of information that was available for map generation.

3. Map Generation

The generation of the digital map of irrigated areas included a variety of steps that depended on the type of data that was available for the respective country. Figure 3 gives an overview of the map generation process. First, the location of irrigated areas within each country was determined. For 144 countries, this was done by digitizing paper maps with the outlines of irrigation areas. These outlines were scanned and georeferenced. For nine countries, the probable location of irrigated areas was derived from either maps of rice production areas, maps of horticultural areas or maps of agricultural areas (in the case of Scandinavia). For 19 mostly small countries with irrigation, no information on the location of irrigated areas was available, and the irrigation was assumed to be either equally distributed or located along large rivers.

Using ARC/INFO, a raster of 5' geographical longitude and 5' geographical latitude was positioned over the generated polygon map. For each of the 4320 x 2160 cells, it was determined whether the cell is irrigated or not. If more than half of the cell area was covered by a polygon, the cell was assumed to be irrigated. As a result of the rasterizing

Table 1. Countries, their irrigated areas and data used to derive the distribution of irrigated areas within the countries. Ranking is according to size of irrigated area. For all countries except China and USA, FAO data on irrigated area per country was taken into account

Rank	Country	Irrigated area [km²]	Data source
1	India	501,020	National irrigation map (Central Board of Irrigation and Power, 1989); irrigated area in 31 federal states (A.R.G. Rao, Central Board of Irrigation and Power, New Delhi, pers. comm., 1998)
2	China	460,030	Irrigated area in 2435 counties (Statistics Publishing House, 1991); digital county boundaries (CIESIN, 1996):
3	USA	234,938	Irrigated area in 3146 counties (Solley et al., 1998); digital county boundaries (USGS, 1998)
4	Pakistan	172,000	National irrigation map (Government of Pakistan, Ministry of Water & Power, 1994); irrigated area in country (FAOSTAT)
5	Iran	72,640	Irrigation map in Achtnich (1980) ; irrigated area in country (AQUASTAT)
6	Mexico	61,000	Irrigation map in Achtnich (1980); irrigated area in 32 federal states (Julio Lorda, FIRCO, Mexico City, pers. comm., 1998
7	Russian Federation	51,580	Irrigation map in Achtnich (1980) Irrigated area in country (AQUASTAT)
8	Thailand	50,040	Irrigation map in Achtnich (1980); irrigated areas in 25 drainage basins (Charoon Kamoiratana, Royal Irrigation Department of Thailand, pers. comm.,1998)
9	Indonesia	45,800	Various irrigation maps; irrigated area in country (FAOSTAT)
10	Turkey	41,860	Irrigation map in Achtnich (1980); irrigated area in country (AQUASTAT)
12	Spain	35,270	Irrigation map in Achtnich (1980); irrigated area in 11 drainage basins (José Hernandez Urrutia, ICID National Committee, pers. comm., 1998)
16	Brazil	31,690	Irrigation map in Achtnich (1980); irrigated area in 27 federal states 1996 (F. A. Rodriguez, Ministry of Environment, Water Resources and Amazon, pers. comm., 1998)
23	Australia	23,170	Various irrigation maps; irrigated area in 8 federal states (Stein, 1986; Australian Department of Primary Industries and Energy, 1998)
33	South Korea	13,350	Irrigation map in Achtnich (1980); irrigated area in 14 federal states 1994 (Yearbook on Land and Water Development Statistics - Korea, 1995, according to pers. comm. of Yung-Duk Lim)
75	Venezuela	1,850	Irrigation map in Achtnich (1980); irrigated area in 24 federal states 1984 (Gonzalo Freites, UCV, Caracas, pers. comm., 1998)
	World	2,549,093	—

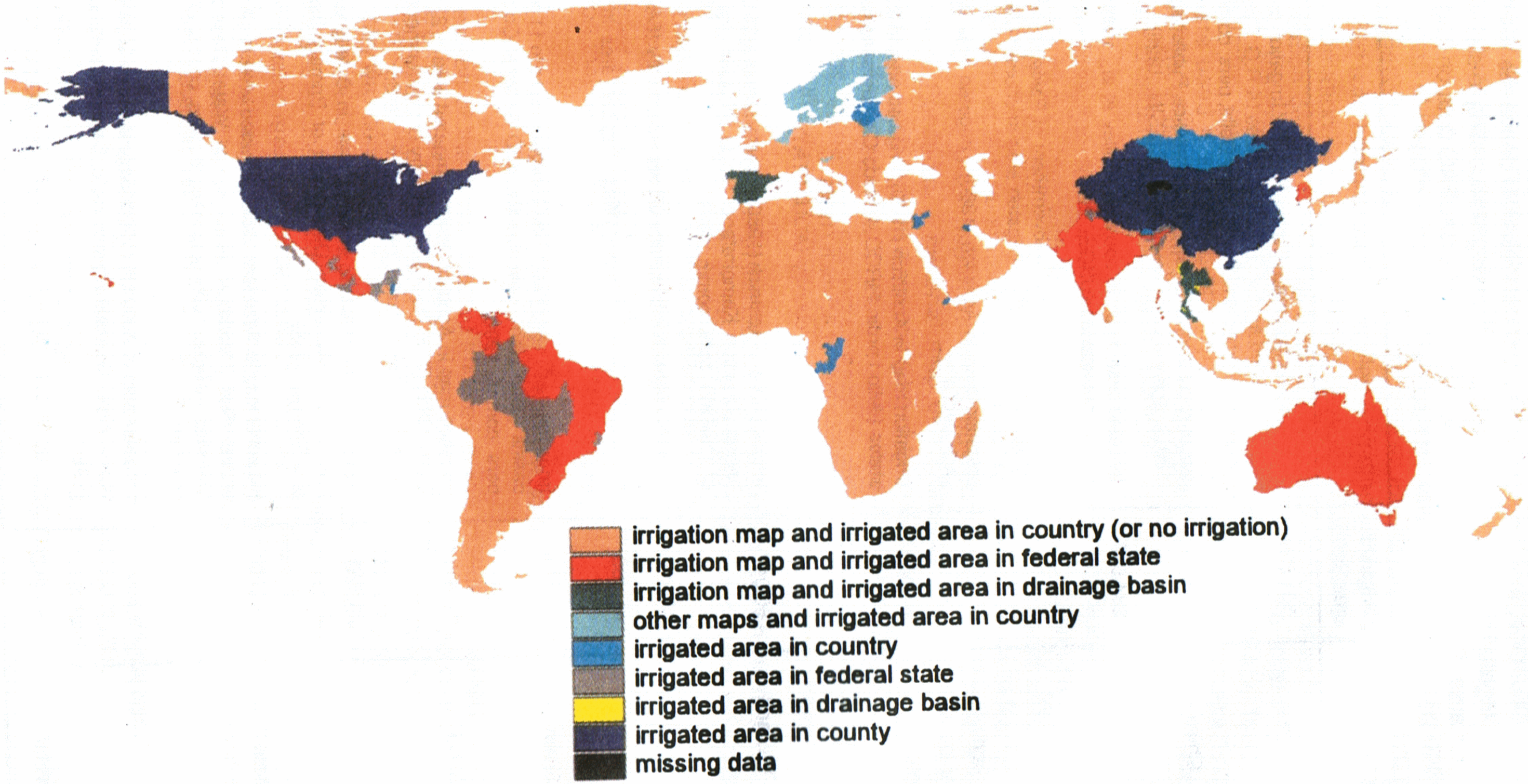

Figure 2. Map and data sources used for the global map of irrigated areas

Table 2. Fraction of irrigated area in global map according to the type of information used

Type of information	Number of countries	Percent of global irrigated area
Irrigation map plus value of irrigated area per country	136	44.41
Irrigation map plus values of irrigated area per federal state	6	24.58
Irrigation map plus values of irrigated area per drainage basin	2	3.32
Other map (e.g. map of rice fields) plus value of irrigated area per country	9	0.57
Value of irrigated area per country	19	0.10
Values of irrigated area per county	2	27.02

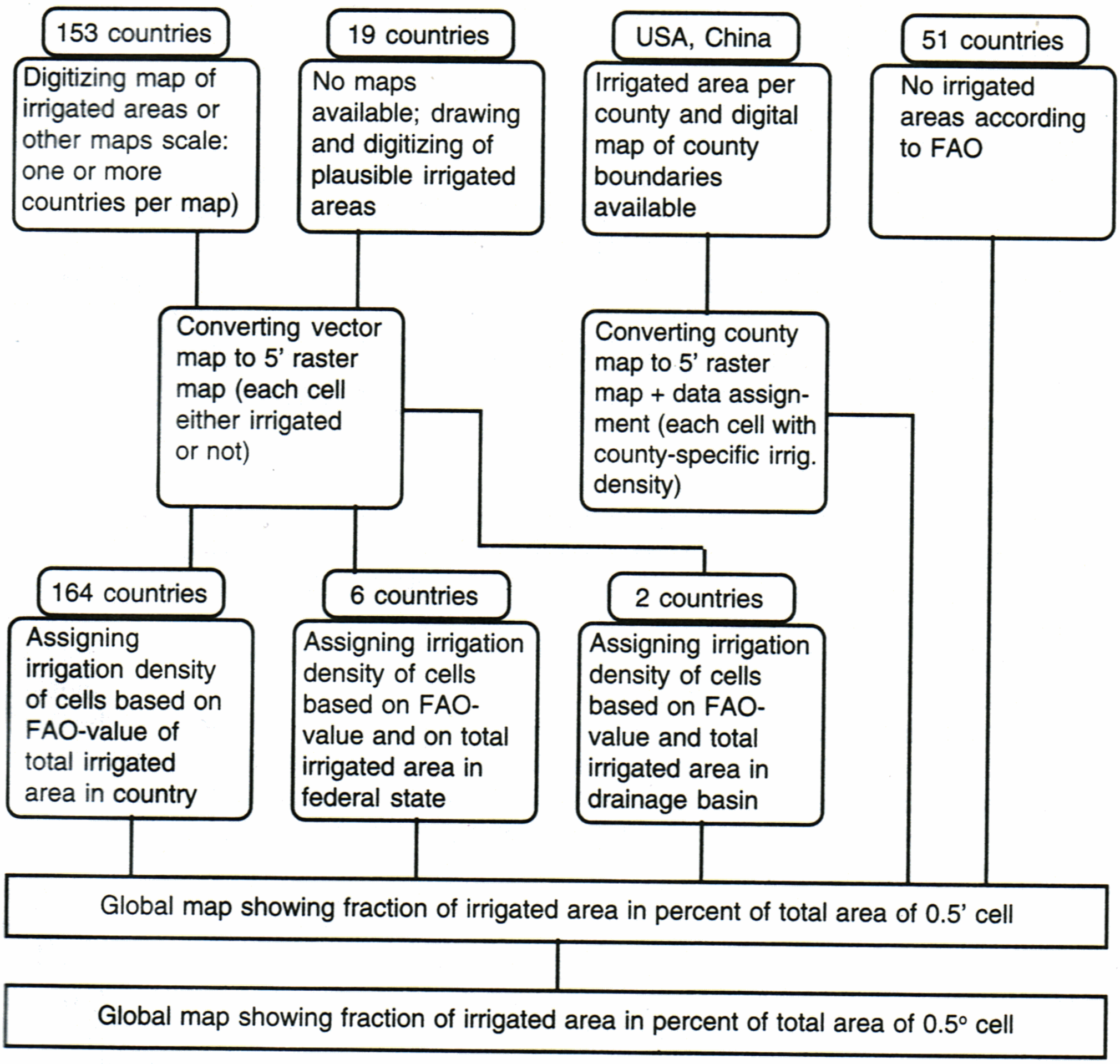

Figure 3. Flow diagram describing the generation of the global map of irrigated areas

process, some small irrigated areas disappeared. In reality, only very few 5' cells (corresponding to areas of 9.25 km by 9.25 km at the equator) are 100% irrigated. Therefore, in the next step, the irrigation density of each 5' cell was modeled using data on the total irrigated area within a spatial unit, i.e. the country, the federal state or the drainage basin (Figure 2).

For 164 countries, for which only country data were available, the 5' irrigation density *d*, i.e. the fraction of a 5' cell area that is irrigated, was determined by comparing the sum of the areas of all irrigated cells $area_{irr\_cells}$ within a country to the total irrigated area $area_{irr\_total}$ of the country (FAO data). Thus, with an exception discussed below, the same irrigation density is assigned to all cells within a country. The irrigation density *d* is computed as :

$$d(country) = 100 \frac{area_{irr\_total}(country)}{\sum area_{irr\_cells}(country)} \quad (1)$$

The cells were related to countries by converting the global "Administrative Unit Boundaries" map of ESRI (1996) to a raster map of 5' resolution.

When adding up the areas of all the irrigated 5' cells within a country, the sum was mostly much larger than the total irrigated area of the country $area_{irr\_total}$, as provided by FAO, and thus the irrigation density is less than 100%. After assigning an irrigation density according to Equation 1, the total irrigated area within a country is equal to the FAO-value. In 13 countries, however, the FAO values were higher than the sum of the areas of the irrigated cells. In small countries, this could be due to the rasterizing process, while in the case of large countries, the irrigation maps must be assumed to be outdated. In these 13 countries, the irrigation density of all irrigated 5' cells was set to 100%, and the neighboring cells were assigned to be also irrigated, with the appropriate irrigation density, such that Equation 1 was fulfilled.

In the case of 6 countries (India, Mexico, Brazil, Australia, South Korea and Venezuela), data on the total irrigated area in each federal state of the country were available. In these countries, irrigation densities for each federal state were computed such that the sum of the irrigated area of all the cells within the federal state was equal to the total irrigated area within the federal state. The cells were related to the federal states by using the "Administrative Unit Boundaries" map of ESRI (1996). Furthermore, the irrigation areas and thus the irrigation densities within each of the federal states were adjusted such that the total irrigated area within each of the six countries was equal to the FAO country value for 1995. Table 3 provides an overview of the methods that were used to harmonize the irrigation map information and the data on irrigated area in each federal state. Equation 2 shows how the irrigation density within each federal state was computed in case 1 of Table 3.

$$d(fed.state, country) = 100 \frac{area_{irr\_total}(fed.state)}{\sum area_{irr\_cells}(fed.state)} \frac{area_{irr\_total}(country)}{\sum area_{irr\_total}(fed.state)} \quad (2)$$

The procedure to determine the irrigation densities in Thailand and Spain, the countries for which total irrigated areas in drainage basins were available, was rather similar (replace "federal state" in Table 3 and Equation 2 by "drainage basin"). The only difference was that the drainage basin boundaries were not available in digital format but had to be digitized first.

Table 3. Methodology for assigning irrigation densities based on data of total irrigated area within a federal state (on 5' raster map).

Case	Condition	Method
1	Sum of the cell area of all irrigated cells is larger than the adjusted state value	Irrigation density of all irrigated cells is computed according to Equation 2
2	Sum of the cell area of all irrigated cells is larger than 0 but smaller than the adjusted state value	Irrigation density of all irrigated cells is set equal to 100%. Irrigation is extended to neighboring cells, which obtain adjusted irrigation densities such that the sum of all irrigated areas is equal to the state value
3	No irrigated cells (based on irrigation maps) but state value larger than 0	Homogeneous distribution of the total irrigated area of the state to all cells within the state

For both China and the USA, lists of total irrigated area per county as well as digital maps of the county boundaries were available. This information was used to determine the irrigation densities on the 5' raster map. First, the digital county maps (polygon maps) were converted to 5' raster maps, such that each cell belonged to a county. The total irrigated area of the county was then equally distributed among all cells belonging to the county. No corrections with respect to the FAO country values were made.

Finally, the generated global 5' map was aggregated to a 0.5° by 0.5° grid (Figure 3). This was done by summing up the irrigated areas within the 36 5' cells that belong to a certain 0.5° cell.

4. Discussion of the Map Quality

The global map of irrigated areas shows the areas that, around 1995, were equipped for irrigation. In general, these areas are larger than those that were actually irrigated in 1995. In Africa, about 18% of the area equipped for irrigation is not irrigated (FAO, 1995), and in the Near East, it is 16% (FAO, 1997a). Of course, these numbers will vary from year to year, but no pertinent information is available. For individual countries, the values range from 0% (e.g. Egypt and Kenya) to 90% (Benin). In Brazil, 19% of the area equipped for irrigation was not irrigated in 1995 (Griesinger, Ministry of Environment, Water Resources and Amazon, Brazil, personal communication, 1998).

The quality of the generated global map of irrigated areas depends on the quality of used base data and the errors that occurred during the map generation. The latter are mainly caused by :

- the rasterizing process (e.g. irrigated areas which covered less than 50% of a 5' cell disappeared);
- the positioning of irrigated areas in countries without irrigation maps;
- the assumption that the irrigation density within a spatial unit (e.g. a country) is constant.

The uncertainty resulting from errors in the map generation process is considered to be lower than that resulting from the (low) quality of the used input data, in particular :

- the total area equipped for irrigation per country as provided by FAO;
- for China and USA, the national compilations of irrigated areas per county;
- the maps of Achtnich (1980) and others.

The quality of these data is discussed below :

The reliability of the FAO data on total irrigated area per country varies greatly (comp. e.g. FAO, 1995). Most countries who report to the FAO do not have a register of irrigated areas or good national statistics. It seems that often little knowledge about the location of small-scale private irrigation exists, and that sometimes these irrigated areas are not taken into account by the national statistics. Besides, there are discrepancies between country values provided by FAOSTAT and AQUASTAT, respectively. According to Jean-Marc Faurès from FAO (personal communication, 1998), AQUASTAT values should be taken if the long time series provided by FAOSTAT are not required. Therefore, values from AQUASTAT were selected if available. As an example, for Azerbaijan, FAOSTAT gives a value of 10,000 km² for 1995, while AQUASTAT lists 14,531 km² for the same year. Although the data are listed as representative for 1995 (in the case of FAOSTAT data) or close to 1995 (in the case of AQUASTAT), some values are only estimates that are derived from much older data (e.g. Angola from 1974).

One should assume that the best available data are the data on irrigated area per county, for China and the USA. However, the International Water Management Institute considers the quality of the Chinese county data to be only mediocre (Ian Makin, personal communication, 1999).

A large part of the used irrigation maps are from Achtnich (1980), who mostly modified other authors' maps from the years 1963 to 1970. According to FAO, in 1970, the global irrigated areas only amounted to 65%, and in 1980, to 81% of the area irrigated in 1995. More recently equipped irrigated areas are not represented by the maps, and the mapped irrigation in 1995 is therefore probably not scattered enough, and too localized as compared to the real situation. In addition, when the polygon map of irrigated areas is rasterized with a resolution of 5' by 5', irrigated areas with less than 20 - 42 km² disappear as they are smaller than half a 5' cell.

In order to obtain a coarse estimate of the applicability of Achtnich's maps for estimating the locations of irrigated areas in 1995, the Achtnich (1980) maps for USA, China and India were compared to the newer information that was used to derive the global map of irrigated areas (USA: county data of 1995, China: county data of 1990, India: map of 1989 + federal state data of 1992/93). The correspondence between the Achtnich maps

and the global map of irrigated areas is rather good. All the areas that are shown as irrigated by Achtnich are areas with a high irrigation density on the digital map, and most of the areas with an irrigation density greater than 10% in the digital map are represented in the Achtnich maps. However, large irrigated areas in the Southeast of the USA (Arkansas, Missouri and Georgia) and in the state of Szechuan in China would be missing if we had relied on the Achtnich map. Apparently, these irrigation areas were newly implemented after 1970; between 1970 and 1995, irrigated areas in the USA and China increased by 34% and 31%, respectively (FAOSTAT data).

What is obvious from the comparison of the county maps for China and the USA with the Achtnich maps is the strong concentration of irrigated areas that occurs when a map with outlines of the (main) irrigated areas is used to derive the spatial distribution of irrigated areas within a country. On such a map, small-scale irrigation is necessarily disregarded. Thus, due to this and due to the implementation of new irrigation since 1970, the real irrigated areas are expected to be more scattered than on the generated data set of irrigated areas (except for China and the USA).

Due to the described uncertainties of the input data and the inaccuracies resulting from the map generation process, it is appropriate to aggregate the 5' map to a map with a resolution of 0.5° by 0.5°. Besides, spatially explicit global modeling is often done on a 0.5° grid.

In summary, the information provided by the global map of irrigated areas is still rather uncertain. This is mainly due to the quality of the data that served as input to the map. However, at the moment, it appears to be the best information available. In our opinion, the presented data set is appropriate for use in global and continental assessments.

5. Further Improvements

In the future, we intend to improve the global map of irrigated areas in 1995 by including more information on the distribution of irrigated areas within countries as provided by national agencies or researchers. This will be done in cooperation with FAO. We would be very thankful for receiving information on the distribution of irrigated areas within the countries for which we could not yet include such information. We also appreciate comments on the quality of the presented map as well as suggestions for improvement.

For most countries, improved national data on the location and extent of irrigated areas are highly desirable. These could be acquired by implementing an irrigation register and by locating irrigated areas with the help of remote sensing. In view of the increasing global problem of water scarcity, international efforts to achieve a better knowledge about current irrigation appear to be worthwhile.

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