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GLOBAL DAM RESERVOIR DATABASE FOR LARGE SCALE HYDROLOGICAL ANALYSIS

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SYNOPSIS

A geo-referenced global dam reservoir database is created by assembling several existing dam inventories and latitude/longitude coordinates that are obtained digitally or taken from printed maps. This database is designed for hydrological applications ranging from a river basin scale to a global scale, and 15,317 dams with their coordinates and 29 dam reservoir attributes are registered on global scale (about 1:1 million resolution) in it. Data of the reservoir/lake in the form of a shoreline polygon is also provided for 4,204 dams. The total storage capacity of the registered dams is 5,594km^3, which is equivalent to the 70% of total storage capacity of all reservoirs and lakes over the world (7,000 km^3). Since a geo-referenced reservoir database which covers whole global area is rarely available, this new database will greatly contribute to making global scale water resource analyses and will have an impact on the assessment of reservoirs on the freshwater systems.

INTRODUCTION

In the 21st century, water resource issues will become more serious due to the increase of water demand caused by both population and economic growth in developing countries and by climatic change. Thus, it is very important to ensure that there are enough water resources and that they are used efficiently. Dam reservoirs play important role for development of water resources. In the 20th century, 45,000 dams of 15m or more in height were constructed all over the world, and a total storage volume developed by these dam reservoirs reached about 7,000km^3 (ICOLD (1)). In addition, the construction of new dams will be continued mainly in developing countries and these dam reservoirs will be used as a valuable source of water supply in these countries.

On the other hand, there is concern that the dam reservoirs will inflict serious damage on natural environment of river channel and riparian zone. The impact assessment of dam reservoirs on river basin environment should be done from the scientific standpoint, and it should be consistent with both water resources development and the conservation of nature. Dynesius and Nilsson (2), one of the pioneers of research in this field showed that 77 % of the total water discharge of the 139 large river system in the northern third of the world (North America, Europe and former Soviet Union) is either strongly to moderately affected by fragmentation of the river channels due to dams and other water related human activities. In addition, the effects of large dam reservoirs on global scale water cycles, river discharges and water resources have also been investigated (Vörösmarty et al. (3), Hanasaki et al. (4))

The dam reservoirs database, which include information about reservoir capacity, surface area of reservoirs, the location of dams, is indispensable for evaluating the impact of dam reservoirs on flow regimes. Several dam/lake reservoir databases are available, however, all these datasets are established for different purposes with different criteria and formats. Furthermore, as reviewed in Lehner and Döll (5), most of the existing dam reservoir inventories provide no location data and only course resolution data is available even if it is registered. Therefore, it is necessary to establish geo-referenced dam reservoir database, which has higher location accuracy to be applied for both regional and global scale hydrological analysis. The combination of this database and a hydrological model will make it possible to assess the impact of dam reservoirs on water and material cycles.

The global dam reservoir database is constructed by assembling several dam inventories and by adding latitude/longitude of each dam. In this way, global distribution of reservoir storage and its hydrological and societal impact can be investigated.

CONSTRUCTION OF GLOBAL DAM RESERVOIR DATABASE

Definition of dam reservoirs

The World Register of Dams 1998 (WRD98) published by International Commission on Large Dams (ICOLD (1)) is used as the basis of new dam reservoir database. In WRD98, a dam of 15m or more in height is defined as a "dam", and embankments for flood protection and coastal levees are not registered as dams. However, reservoirs of 3 million m^3 or more in storage capacity are also registered as reservoirs even if their dam height is lower than 15 m. According to the definition in WRD98, if a dam height is higher than 15m or storage capacity of reservoir is more than 3 million m^3, it is regarded as dam reservoir in this study. In addition, reservoir with larger storage capacity than 0.1 km^3 is defined as "large dam reservoirs". This new database is mainly focus on large dam reservoirs, and including the data of dam reservoir features and location.

Existing dam inventories and map

The datasets used for constructing new database are listed in Table 1, in which the name, publisher and spatial coverage of each datasets are listed. WRD98 (with data "updating 2000 for china") includes the records of 27,989 dam reservoirs with 29 attributes (ex. reservoir capacity and area, year of completion), and this is the most comprehensive dam inventory that is currently available and accessible. Thus, most of dam reservoirs contained in the new database are taken from WRD98 except for the geographic coordinates of dam. Since WRD98 has no latitude/longitude information of dam reservoirs, published datasets or digital maps (Digital Chart of the World (DCW) (6), Operational Navigation Chart (ONC) (7)) are used to obtain the geographic coordinates of dams. The digitizing of the dam location is carried out with the greatest circumspection to improve the precision of location data rather than other lake/reservoir datasets (ex. World Lake Database (8)). WRD98 contains nation-wide data which is provided from member countries of ICOLD; therefore, reservoir data for non-member countries are not registered. For these countries or regions other datasets (ex. Geo-referenced database on African dams, FAO (9)) are used for filling the gap of data coverage.

Table 1 Overview of existing dam reservoir datasets used for construction of geo-referenced global reservoir database. (Characteristics of this database is also listed in this table)

Name of Data Set	Publisher/ Organization	Spatial Coverage	Lat./Lon Coordinates	Reservoir Attributes	Data Records
World register of dams 1998	ICOLD	Global	×	○	27,989
Digital chart of the world	ESRI	Global	○	×	6,516
Dams and storages database	Geoscience australia	Australia	○	○	846
Geo-referenced database on African dams	FAO	Africa	○	○	1,192
Digital National Land Information (W01-07P)	MLIT	Japan	○	○	3,143
Summary of selected characteristics of large reservoir	USGS	US	○	○	2,708
Major dams	USGS	US	○	○	7,782
World lake database	ILEC	Global	○	○	730
Geo-referenced global reservoir database	Univ. of Yamanashi	Global	○	○	15,317

Table 2 The map and atlas used for acquiring the geographic coordinates of each dam

Name of Map/Atlas	Organization / Publisher	Coverage	Scale
Operational Navigation Chart	NIMA / FAA	Global	1,000,000
World Aeronautical Charts	The Canada center for mapping	Canada	1,000,000
Bertelsmann World Atlas	Mairs Geographischer Verlag Ostfiklern	Global	1,000,000～4,000,000*
Time/WORLD ATLAS	TIMES BOOKS	Global	1,000,000～4,000,000*
Comprehensive Atlas of The World	HAMMOND INCORPORATED	Global	1,170,000～21,000,000*

*: different in each page/map

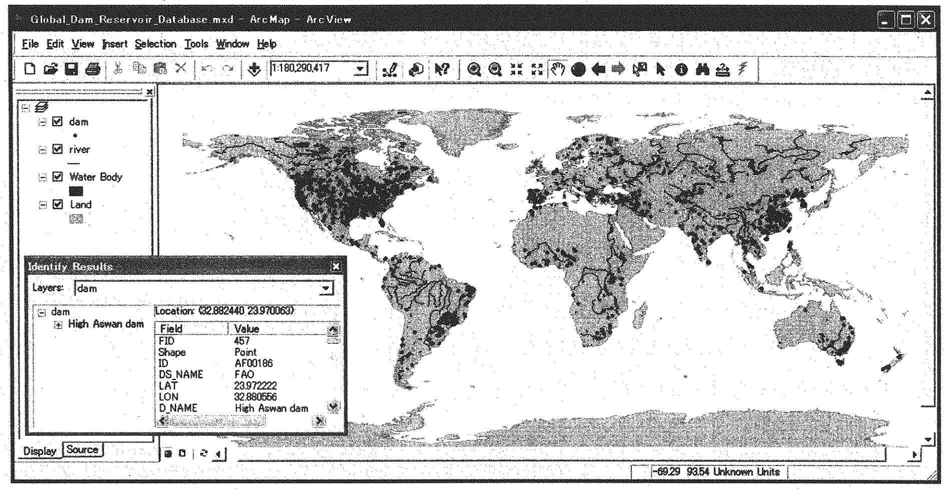

Fig.1 Illustration of Global dam reservoir database on GIS
(Dam Reservoirs with storage capacity ≥ $0.5km^3$ are displayed)

Construction of Dam reservoir database

a) Acquisition of location data and relation with attribute data

The geo-referenced dam reservoir database is constructed by means of the following procedure. Dam location (latitude/longitude) is obtained from 1/1,000,000 ONC map or DCW GIS data. After the geographic coordinates of dams are obtained, the name of the dam or reservoir is identified from an atlas or printed maps. Dam attributes from WRD98 and acquired location data are related each other based on the name of dam and reservoir, name of river, and nearest city from dam. Where, a reciprocal relationship is found, a special data flag is added for secondary dams to avoid the possibility of double counting reservoir storage and areas. The available geo-referenced dam database in the US, Japan and Australia are also merged into a new database. Finally, all data prepared for each region are integrated and the global dam database is completed (Fig 1.).

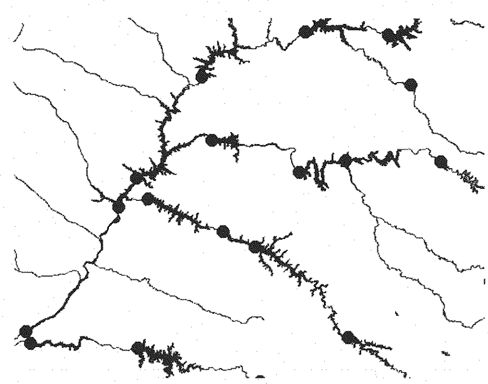

Fig. 2 Exemplification of shoreline polygons in Brazil
● : Dam body, Shaded area: Reservoir surface

Currently, 2,341 large dam reservoirs (storage capacity ≥ 0.1 km^3) are registered in this database and the total storage capacity of these large dam reservoirs is $5{,}445km^3$. Also, the total number of registered dams is 15,317 and their total storage capacity is 5,594 km^3.

b) Shoreline polygon data

In this database, dam location indicates the location of the dam body itself, not the location of reservoir. However, the extent of water surface is important for making an analysis of evaporation loss from the reservoir and for satellite monitoring of dam reservoirs. Shoreline data is also prepared for most of large reservoirs (storage capacity ≥ 0.1 km^3) by means of following procedure:

1) Overlaying dam reservoirs/lake and digital map (DCW, ONC) on GIS to identify the corresponding water body for each dam.

2) Based on DCW, shoreline data for each dam is provided by using GIS. If no corresponding water body shoreline is included in DCW, the shoreline polygon is digitized from ONC.

3) Each shoreline data is related to point data of dam on GIS.

Totally, 4,204 shoreline polygon data is provide and registered in the database (ex. Fig.2).

c) Check of Error data

In the most of existing dam dataset, some incorrect data are included due to typographical errors. It is difficult to find this type of error data, however, obvious error data is identified and corrected by checking the following dimensions:

1) Dam Height [*H*] > 335m: The highest dam in WRD98 is Rogun dam (335m), and a dam higher than that is considered as error data.

2) Area of Reservoir [*A*] > 8,482km^2: The Akosombo dam reservoir has the largest area of water surface (8,482km2) in WRD98, and a larger water area than that is regarded as error data.

3) Reservoir Capacity [*V*] > 180.6 km^3: The larger storage capacity than Kariba dam reservoir, which has a storage capacity of 180.6 km^3, is considered to be error data.

4) $D > H$: The *V* divided by A is an average water depth of reservoir [*D*]. If *D* is larger than dam height *H*, A or *V* would have some problems because *D* should not be higher that *H*.

5) $D < 0.1$m: Unrealistically small *D* is regarded as error.

These error data are corrected by comparing them with other datasets (ex. USGS (10), UNH (3) and ILEC (8) data) or other data from the web pages of dam management agencies.

SUMMARY OF DAM RESERVOIR DATABASE

Dam location

The dam reservoir database constructed in this study includes data of 15,317 dams, and 15,034 of which have dam location data. The existing dam datasets are merged into the database in Africa (9) and Brazil (11), and location data are missing for some dams in these datasets. The precision of the location data is about 1:1,000,000, which is equivalent to the accuracy of ONC and DCW. It should be noted that location data for the dam, which could not identified in ONC and DCW, is obtained from printed maps with a different scale and accuracy. This result in a different precision of location data for each data points, therefore, the scale of map used to acquire dam location is also added as attribute of each data point.

The Table 3 shows the findings of a comparison made between dam reservoir database and WRD98 in terms of the number of registered dam. Where the "recorded rate" is defined as the ratio of the number of registered dams against dams in WRD98. The recorded rate on global scale is about 55%, however, in terms of storage volume, 95.5% for very large dam reservoirs (storage capacity $\geq$ 10km^3) and 80.4% for large dam reservoirs (storage capacity $\geq$ 0.1 km^3). This suggests that most of large dam reservoirs are registered in the database. In the North America and Australia, the recorded rate is over 100%. In WRD98, only the dams higher than 15m are registered, however, some established datasets that include smaller dams with heights of less than 15m are merged into the database of these regions.

Table 3 Recorded rate of dam reservoirs for each continents

Continent*	All Data (%)	≥10km³ (%)	≥1km³ (%)	≥0.1km³ (%)
AFRICA	83.7	100.0	83.7	92.5
AMERICA N.	106.7	138.5	136.5	143.6
AMERICA S.	38.6	88.0	71.6	57.9
ASIA	35.2	78.8	62.7	50.6
AUSTRAL-ASIA	132.0	25.0	78.9	83.6
EUROPE	14.4	93.3	52.4	42.3
GLOBAL	55.0	95.5	85.9	80.4

*following to the definition in ICOLD(1998)

Table 4 Recorded rate of shoreline polygon data

	the num. of shorelinepolygon	the num. of dam reservoir	recorded rate(%)
≥0.1km³	1509	2341	64.5
≥0.5km³	736	956	77.0
≥1km³	523	599	87.3
≥5km³	154	172	89.5
≥10km³	100	108	92.6
All data	3688	15317	24.1

Table 5 Recorded rate of major dam reservoirs attributes

	Reservoir Capacity	Reservoir Area	upstream Catchment Area	Year of Completion
the num. of registered data	14390	10282	6924	11001
recorded rate (%)	93.9	67.1	45.2	71.8

Shoreline data

3,688 dam reservoirs out of 4,204 shoreline data are assigned to dam attributes of the database. As shown in Table 4, in terms of the number of dam reservoirs, shoreline polygons are prepared for 24.1 % of all dam reservoir, however, shoreline data is provided for 92.6 % of very large dam reservoirs (storage capacity ≥ 10km^3) and 87.3 % of large dam reservoirs (storage capacity ≥ 0.1 km^3), respectively. In terms of storage volume, the total storage capacity of reservoirs with shoreline data is 4,884km^3, and this is equivalent to 87.3 % of total storage capacity of all registered dam reservoirs in our database (5,594km^3).

The poor availability of shoreline data for small reservoirs is mainly due to the scale of base map. DCW or ONC, which are used as base maps for the digitization of the shoreline polygon, have a scale of 1:1,000,000, so it is difficult to find small lakes and reservoirs (storage capacity ≤ 0.1 km^3) on this map. Obtaining the shoreline polygon for recently constructed dam reservoirs is also problem because DCW and ONC were prepared on the basis of field surveys between the 1970s and 1990s and most of dam reservoirs constructed after 1990s are not represented in these base maps. In addition, as pointed out in Lehner and Döll (5), Birkett and Mason (12), the shape and extent of water surface on DCW and ONC are sometimes inconsistent with present situation for some lakes and reservoirs, such as Lake Chad where the water level of the lake has dropped in recent years. For these lakes and reservoirs, shoreline information should be corrected by using recent published maps or satellite images.

Attributes of dam reservoir

In the database, 29 attributes are given for each data point: continent, country, state/province/county, nearest city, name of river, name of dam, name of main dam, name of reservoir, year of completion, dam type, foundation, height of dam, length of dam, volume of dam body, materials of dam body, reservoir storage capacity, effective storage capacity, area of reservoir, perimeter of water surface, purpose of dam, upstream area, spillway capacity, spillway type, owner, consultant, contractor, secondary dam, multi-national dam, condition of dam. Table 5 shows the percentage of completed data for principal attributes, where the percentage of completion is defined as the relative ratio to the number of data points in WRD98. The attributes of the "dam location" and "name of dam" are almost completed. On the other hand, completeness for "area of water surface" and "year of construction" are around 70 %, and this is due to error data or data missing from these attributes in the WRD98 and other datasets included in the database.

DISTRIBUTION OF WORLD DAM RESERVOIRS

Global distribution of dam reservoirs

Fig.3 shows the global distribution of registered dam reservoirs in the database where only reservoirs larger than $0.5km^3$ in volume (956 dam reservoirs) are plotted. The latitudinal and longitudinal distribution are also shown in this figure. Many large dams are located in the regions of the North America, Russia and China, and 30 to 60 degree latitudinal band and longitude of –125 to –65 and 130 to 155 degree. Fig. 4 shows the total reservoir capacity and area for world major river basins, where the boundary of river basins are obtained from TRIP (Oki et al. (13)). The huge volume of reservoir storage is developed in the Mississippi (about $430km^3$), the Parana (about $350km^3$) and the Enisei ($310km^3$). Fig. 5 provides the percentage of evaporation loss from reservoir surface to total storage capacity of the reservoir. For each reservoir, evaporation loss is calculated by using reservoir area from this database and climatology of potential evaporation (Funada et al. (14)). Where, the Penman method is applied to estimate potential evaporation from water surface of each reservoir, 0.5 degrees grid climate data (CRU CL1.0 (New et al. (15))) is used as input data. The percentage of evaporation loss varies depending upon climatic zones and the surface area of reservoirs, and more than 20 % of evaporation loss was observed in arid/semi-arid regions or some reservoirs with a large water surface.

The increase of river water residence time caused by dam reservoir is shown in Fig. 6. The residence time for each river basin is calculated as total storage capacity of reservoirs within the river basin divided by annual total river discharge at river mouth (UNH/GRDC (16)). Just as Vörösmarty et al. (3) observed, we also observed remarkable increases of residence time as shown from these results. An increase of more than six months of residence time was found in some river basins.

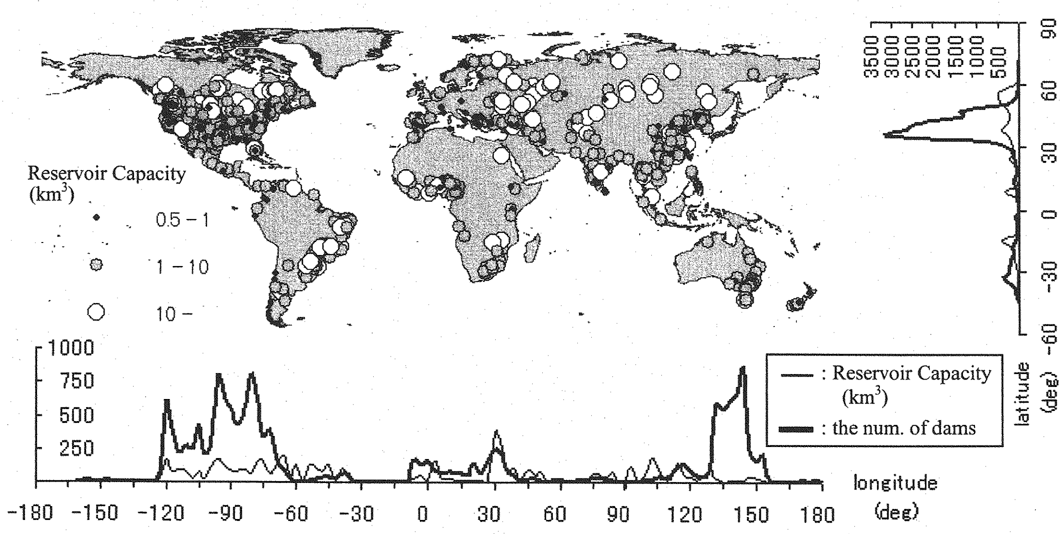

Fig. 3 Latitudinal/Longitudinal distribution of reservoir storage
(Dam Reservoirs with storage capacity $\geq 0.5km^3$ are displayed on the map)

Evolution of dam construction in 20^{th} century

The construction of the number of dams, the total storage capacity and the area of reservoirs are shown in Fig. 7. The total number of dams and area of water surface over the globe gradually increased from about 1900 and rapidly grown from 1950s to 1990s. The storage capacity also increased in 1950s to 1990s and no significant development has been observed after 1990s. This indicates that most large dams were constructed in the middle of later part of 20^{th} century. Fig. 8 shows the change of storage capacity per capita from the year of 1950 to 1990. A remarkable increase was observed in the Russia, Zambia, Ghana and Paraguay due to a large dams construction (ex. Bratsk in Russia (1964), Kariba in Zambia (1959), Akosombo in Ghana (1965) and Itaipu in Paraguay (1983)) in these countries after the 1950s.

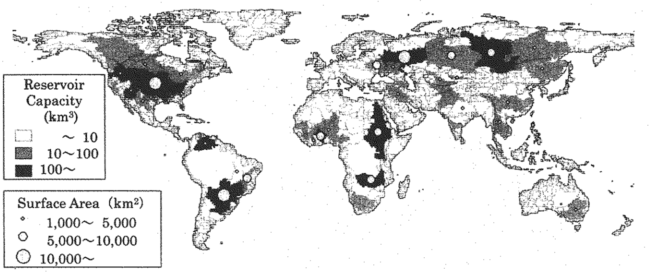

Fig. 4 Total reservoir capacity and area for world major river basins

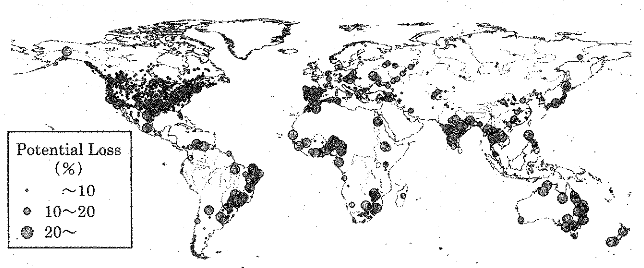

Fig. 5 Evaporation loss from reservoir surface
(percentage of evaporation loss from reservoir surface relative to total storage capacity of the reservoir)

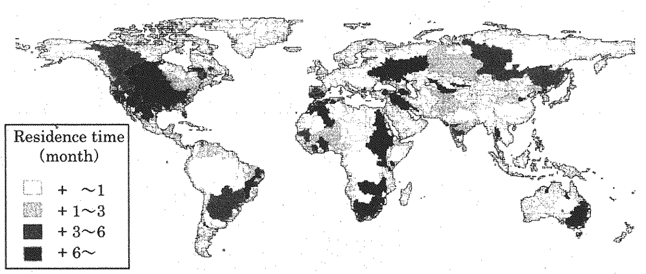

Fig. 6 Increase of river water residence time caused by reservoirs

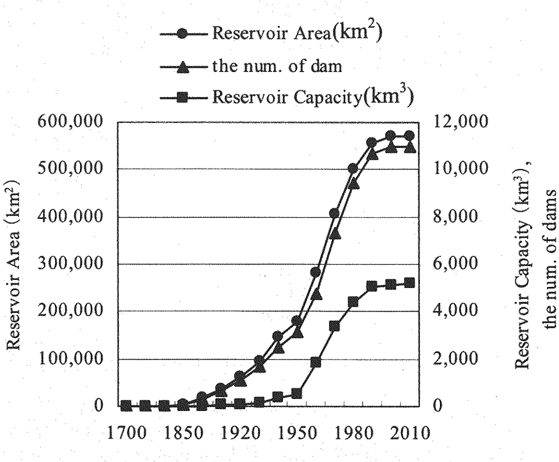

Fig. 7 Development of dam reservoirs from 1700s

CONCLUDING REMARKS

A geo-referenced global dam reservoir database was constructed by compiling some published dam reservoir and lake datasets, and by adding dam location data to these existing dam inventories. In this database, 15,317 dam reservoirs with 29 attributes are registered, and the total storage capacity of registered dam reservoirs is 5,594km^3 and total area of water surface is 346,914km^2. This is equivalent to the 80 % of total storage capacity on all over the world (7,000km^3). In addition, 4,204 shoreline polygons for lake and reservoirs were prepared. In the database, 2,341 reservoirs more than 0.1 km^3 are registered and 60 % of these (1,509) have polygon data of shoreline.

The large number of data included, as described above, is one of the notable features of this database, however, "geo-referenced" data with latitude/longitude coordinates is another distinctive characteristics. This geo-referenced data makes it possible to correspond each reservoir geographically with river basins or stream networks on different spatial scale and units. The overlay analysis of the geo-referenced reservoir data with global GIS and hydro-climate data can be used to quantify the alteration of natural river flow in large river systems (as shown in Fig.6) or sediment retention on continental scale (Vörösmarty et al. (17)) due to human-induced impoundment. In addition, we also hope that this database will contribute to making impact assessments of reservoirs on river flows and the water environment by combining it with a hydro-meteorological model. The hydrological model which considers reservoir operation (ex. Hanaseki et al. (4), Magome et al. (18)) could be a useful tool for estimating the change of flow regime due to dam construction and consequent damages on aquatic and riparian environment. The location and storage capacity data of dam reservoirs is most important and fundamental information is needed for the model simulation, our reservoir database can also be used for that purposes.

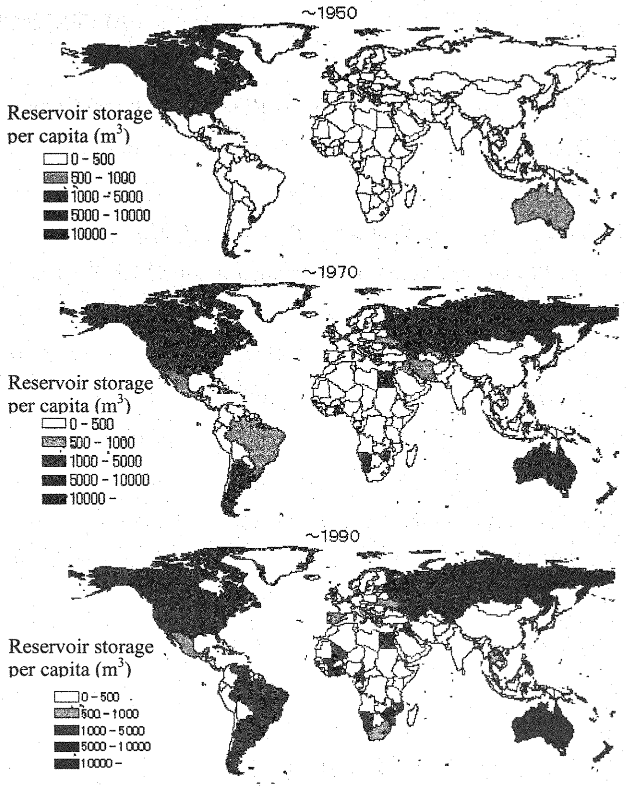

Fig. 8 Transition of national total reservoir storage per capita

However, some problems were found by making a quality assessment of registered data. For example, the number of registered data and completeness of data attributes are different in each region/continent, and shoreline data are prepared only for very large dam reservoirs. Therefore, further improvement of data quality is necessary by means of the following tasks: 1) acquisition of dam location data in the Asia, Europe and South America where the number of registered data is less than other regions, 2) acquisition of shoreline data for medium to small size reservoirs, 3) collecting the data of reservoir area and upstream catchment area of reservoir for filling up of missing data records of these attributes. Furthermore, the release of this database to research community is another important task. Inter-comparison of our database with others (ex. Lehner and Döll) or feedback from users will also contribute to improving the quality of the database. (For more details about data access, contact to magome@yamanashi.ac.jp)

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