Earthquake Hazards and Large Dams in Western China

A Probe International Study

By

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John Jackson is a pseudonym for a geologist who wishes to remain anonymous to protect his Chinese sources.

Executive Summary

By constructing more than 130 large dams in a region of known high seismicity, China is embarking on a major experiment with potentially disastrous consequences for its economy and its citizens. A comparison of large dam locations to seismic hazard zones,[1] for dams that are already completed, currently under construction, or proposed for the Tsangpo, Po, Salween (known as Nu in China), Mekong (Lancang in China), Yangtze, Yalong, Dadu, Min and Yellow river headwaters in western China, indicates that 48.1% of these dams are located in zones of high to very high seismic hazard, 50.5% are located in zones of moderate seismic hazard and only 1.4% are located in zones of low seismic hazard. With respect to power generating capacity, 67.2% of the total megawatt capacity is located in high to very high seismic hazard zones, 32.5% in zones of moderate seismic hazard and only 0.3% in zones of low seismic hazard (see Table 4). Moreover, the rapid rate of construction and the location of some of these dams around clusters of M>4.9 earthquake epicenters, from events that occurred between 1973 and 2011[2], is cause for significant concern. The risk of earthquake damage caused by the region's high natural seismicity is compounded by the risk of Reservoir Induced Seismicity (RIS) which results from the seasonal discharge of water from the region's reservoirs. The risk of earthquake damage to dams is also compounded by the increased risk of multiple dam failures due to the cascade nature of dam spacing.[3]

The purpose of this report is to highlight the urgent need for the Chinese government to ensure that an independent, comprehensive, and expert seismic risk assessment of the extensive dam-building program in western China is undertaken. In order to provide the best possible assessment of the seismic risk hazard of China's current dam-building program, the recommended study should be prepared using mapping software similar to that used in this report but with up-to-date, complete, and precise latitude and longitude locations and size (megawatts) of dams situated within the known seismic hazard zones and in relation to historical temblors over M>4.9. The proposed study would inform risk assessments and investment

decisions, highlight the need for improved safety standards in dam construction and operation and better emergency preparedness, and lead to the cancellation of dams which pose an unacceptable risk to public safety.[4] The proposed study must also be disclosed to China's citizens, press, power companies, financial institutions, and law-makers to ensure that an informed public debate about the risks of China's dam-building occurs, liability for hazards and damages are properly assigned, and safety standards and emergency preparedness procedures are widely disseminated and debated. Due to the rapid rate of dam construction, this proposed study should be completed as soon as possible.

The database of dams built, under construction, and planned for China's rivers used in this study comes from a map prepared by HydroChina prior to 2004 and found on the HydroChina website in 2008, with the data confirmed by more recent surveys as well as Google Earth satellite images. Based on this review, it appears that about half of the dams have not yet been built, but that the pace of construction is rapid.[5] This makes a seismic risk hazard assessment of western China dams all the more urgent.

Introduction

Figure 1 shows the locations of major dams either built, under construction, or proposed for the headwaters of the Tsangpo, Po, Salween, Mekong, Yangtze, Yellow, Yalong, Dadu and Min rivers in western China, relative to the epicenters of large earthquakes (M>4.9), and to zones of high to very high, moderate and low seismic hazard. The locations of these major dams are based on the "ziyuan_b" map on the website http://www.hydrochina.com.cn/zgsd/images/ziyuan_b.gif (Figure 2), published by HydroChina.[6] There are more detailed maps on other websites which show additional dams[7], but these maps do not provide a reference grid or scale for location of these dams, so only the 137 dams shown on the rivers of western China on the "ziyuan_b" map on the rivers listed above are included in this analysis (see Table 1).[8]

The earthquake epicenter locations for all earthquakes within the map area with magnitudes (M) greater than 4.9 (M>4.9) in Figure 1 were obtained from the US Geological Survey earthquake database at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php.[9] M>4.9 was selected as the minimum because earthquakes of this magnitude have been known to cause damage to dams and to other structures (see Table 6).[10]

The USGS global database for the years 1973 – 2011 was utilized in this analysis because, prior to 1973, the location and magnitude of earthquakes in this area were estimated. Furthermore, prior to 1973, the focal point depths of earthquakes were unknown and impossible to estimate, therefore eliminating the usefulness of pre-1973 data in assessing the risk for reservoir induced seismicity caused by dams built in this area (see discussion below).[11] The seismic hazard zones depicted in Figure 1 are adapted from the Seismic Hazard Map published in 1999 by the Global Seismic Hazard Assessment Program of the United Nations (http://geology.about.com/od/seishazardmaps/ss/World-Seismic-Hazard-Maps_16.htm).[12] In this extraordinary exercise, 500 scientists mapped the magnitude of horizontal shaking that can be expected in a given place during a given time span for the entire world.[13] The base map showing major rivers and China's boundary was obtained from Earth Science Resources Incorporated (ESRI) (http://services.arcgisonline.com/ArcGIS/rest/services/Reference/World_Reference_Overlay/MapServer).

A database of cities and towns was constructed using coordinates obtained from Google Earth. The maps and statistical summaries were prepared using ESRI'S ArcGIS 10.0 software. The current status of dams on each river (Table 5) is based on a variety of sources and confirmed (to the extent possible) by close examination of the most recent satellite images by Google Earth.

Analysis

Once the dam, earthquake, and city/town databases were converted to map layers, these layers and the seismic hazard zone map were added to the base map. Table 1 summarizes data for the dams on each river as found in the ziyuan_b map. Table 2 summarizes data for the magnitude of earthquake epicenters and their focal point depth. Table 3 summarizes the percent of dams within each seismic hazard zone for each river and Table 4 summarizes the percent of total megawatt capacity within each seismic hazard zone for each river.

While the risk analysis in this study is based on the ziyuan_b map of 137 dams built, under construction and planned for each of these rivers, in all likelihood this database is incomplete and underestimates the number of dams on these rivers. Table 5 lists 137 dams that are either completed, under construction, or proposed for each river in this region based on those indicated in the ziyuan_b map *and* on the number of dams visible on Google Earth satellite images that have been completed or are under-construction as of December 2011. Table 5 demonstrates that this study's assessment of the risk from dam building in this region is likely to be an underestimate.

Discussion

Overlaying the UN Seismic Hazard Zone map, with HydroChina's "ziyuan_b" dam locations, with USGS data for the location, magnitude, and epicenters of earthquakes in western China has allowed us to produce the seismic hazard maps for western China's dams found in Figures 1 and 6, and the data sets found in Tables 1 – 4. These figures and tables reveal several disturbing patterns.

Figure 1 and Table 3 indicate that 48.1% of all dams built, under construction or planned for construction are located in zones of high to very high seismic hazard, 50.5% are located in zones of moderate seismic hazard and only 1.4% are located in zones of low seismic hazard (Table 3).

Table 4 indicates that 67.2% of the total MW capacity are located in zones of high to very high seismic hazard, 32.5% are located in zones of moderate seismic hazard and only 0.3% are located in zones of low seismic hazard.

In other words, 98.6% of all of these dams, and 99.7% of western China's electricity generating capacity, are, or will be, located in zones with a moderate to very high level of seismic hazard.

Because the damage caused by earthquakes increases with proximity to the epicenter, and increases as focal point depth decreases — the seismic waves that cause vertical and horizontal ground shaking attenuate with distance — the location of large dams near clusters of M>4.9 earthquake epicenters (Figure 1), and especially around shallow earthquakes with magnitudes of 4.9 or more (Figure 6), is cause for grave concern.[14]

It is also important to note that, based on the 1973-2011 USGS earthquake database, on average there have been nine M>4.9 earthquakes in this area of western China every year.

Figures 3 and 4 illustrate why this is so: Figure 3 (the Geological Map of Nujiang, Lancang and Jinsha Rivers Area, Ministry of Geology and Mineral Resources, Chinese Academy of Sciences, 1980) shows the high number of active faults in this area (with faults and rivers highlighted). Figure 4 (Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements, Gan et al., 2007) shows that the relatively rapid northward motion of the Indian subcontinent is creating a large regional stress field in western China and causing crustal motion of 30 -50 mm/year to the north, northeast, east and southeast.[15]

The seismic hazard zones developed by the UN Global Seismic Hazard Assessment Program are defined by projections of peak ground acceleration (PGA). PGA is a measure of the horizontal shaking of solid rock due to surface seismic waves. The high to very high seismic hazard zone has a PGA of 2.4 to 5.6 meters per second squared (m/s^2), the moderate zone PGA is from 0.8 to 2.4 m/s^2, and the low zone PGA is from 0 to 0.8 m/s^2. The maximum PGA (5.6 m/s^2) is more than half of the acceleration due to gravity at the earth's surface (9.8 m/s^2, a vertical force often called One G). The projected PGA values have a 10% probability of being exceeded within 50 years of 1999 (i.e. 2049). In all likelihood, the area of western China with high to very high seismic hazard would be even larger if data subsequent to 1999 had been incorporated in the UN's Global Seismic Hazard Assessment Program's seismic hazard map. This is because the Global Seismic Hazard Assessment Program map, completed in 1999, was based on 26 years of data. If it had included data from 1999 to 2011, the map would then be based on 38 years of data, including two of the largest earthquakes (Wenchuan in 2008, at M=7.9, and Yushu in 2010, at M=6.9), both of which occurred in areas assessed in 1999 as moderate seismic hazard. If 38 years of data had been available for this analysis, these areas would likely have been classified as high to very high seismic hazard.

Moreover, if the database had covered a period of time equal to the projected life of most dams (about 150 years, or from 1850 to 1999), and not just the 26 years considered by the UN study, it is highly probable that the *entire* area of western China would be considered a high to very high seismic hazard zone. Even 150 years of data is statistically insignificant from a geological perspective, and if seismic data were available going back millions of years, there is little doubt that the high to very high seismic hazard zone would cover the entire region of western China.[16]In the area of western China under discussion, nine of the 137 dams built on the aforementioned nine rivers were constructed prior to 2000, and were located mostly on the Yellow, Min and Mekong rivers. Based on Table 5, an additional 26 dams have been completed since then, another 33 are under construction as of 2011, and another 69 are slated for completion over the next few decades. This rapid rate of large dam construction in a highly seismic area is the primary reason why a review of the dam construction program, in this region, is urgently needed.

The main purpose of seismic hazard maps today is to provide a basis for urban construction codes, but they can and should be used for dam building codes. To assess the effects of earthquakes on existing dams,[17] in 2005 the US Federal Emergency Management Agency (FEMA) published “Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams” (http://www.damsafety.org/media/Documents/PDF/fema-65.pdf). In 2011 the US Federal Energy Resources Commission (FERC) added Chapter 13, Evaluation of Seismic Hazards, to its publication “Engineering Guidelines for the Evaluation of Hydropower Projects” (http://www.ferc.gov/industries/hydropower/safety/guidelines/eng-guide/chap13-draft.asp#skipnav).

These documents describe different types of dams and the various types of damage that can be caused to them by earthquakes. For example, consider that the densities of dams are different from the density of the ground upon which they rest and from the water in their reservoirs. Consequently they vibrate at a different frequency than the ground vibrates during an earthquake and at a different frequency than the water in their reservoirs. As a result, massive concrete dams, such as those being built in western China, will most likely sustain damage at their contacts with the earth (at their base and sides) and with their reservoirs, especially near the crest where the dam is thinnest and least competent.[18] Additional information is available from the US Association of Dam Safety Officials (http://www.damsafety.org/).

Examples of recent seismic damage to dams in China include the 2008 M=7.9 Wenchuan earthquake about 100km (60 miles) northwest of Chengdu and the 2010 M=6.9 earthquake near Yushu on the upper Yangtze (see locations on Figure 1). The 2008 Wenchuan earthquake killed an estimated 80,000 people and damaged the Zipingpu Dam, which is located on the Min River. This earthquake caused cracks in the dam structure and collapsed walls at the power plant. As well, the generators had to be shut down and the reservoir emptied to assess damage. Landslides into the reservoir caused a significant amount of damage to buildings along its banks. This 156-metre high dam subsided up to 1 meter and was displaced downstream up to 60cm. The 2010 Yushu earthquake destroyed the town of Yushu and damaged three dam complexes, including the Xihang, Dangdai, and the Changu dams, all located on a Yangtze tributary.[19]

Another risk factor must also be considered: reservoir induced seismicity (RIS). RIS occurs when two major factors are present: 1) a regional stress field acting on an existing fault system; and, 2) seasonal fluctuations of reservoir levels (*Reservoir-Induced Earthquakes*, H.K. Gupta, 1992 New York: Elsevier). Although, no large dams are known to have failed due to RIS, there is clear evidence that dams can trigger seismic activity and, in turn, be damaged themselves by the self-induced temblors. For example, the Zipingpu dam damaged by the 2008 Wenchuan earthquake is now thought to have triggered the M=7.9 earthquake (see this article for details). H.K. Gupta identifies four cases in which dams caused M=6.1 to M=6.3 earthquakes (RIS) that were, in turn, damaged by the quakes, as well as six dams that caused M=5.0 to M=5.7 RIS and resulted in damage to nearby structures (see Table 6). For example, the Xinfengjiang Dam in southeast China (Lat 23.73, Lon 114.65) was seriously damaged in 1962 by the M=6.1 earthquake it triggered (Reservoir-induced Seismicity in China, Chen and Talwani, 1998).

The basic premise of RIS is that a full reservoir lubricates active faults by increasing pore pressure, and that subsequent reservoir water drawdown reduces the friction caused by the mass of the reservoir. In western China, there is a large regional stress field causing crustal motion of 30-50 mm/yr to the north, northeast, east and southeast due to the relatively rapid northward motion of the Indian subcontinent (Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements, Gan et al., 2007) as illustrated in Figure 4. In addition, due to the seasonal variation in river discharge in this area, reservoirs will fill in the late summer and early fall and decline throughout the winter and early summer (see Figure 5, http://en.wikipedia.org/wiki/File:Yangtze_River_flow_rate_at_TGD_site.JPG).

Most RIS generated faults have a focal point less than 10 km deep. Figure 6, which overlays the maps of dam locations, seismic hazard zones, and the locations of earthquake epicenters with <10 km focal point depths based on USGS data, reveals eight clusters of large dams and shallow earthquakes. These clusters of dams and shallow earthquakes are located on the Yangtze near Yushu, Batang, Lijiang and Panzhihua, on the Yalong near Garze, on the Min near Wenchuan, on the Yellow west of Lanzhou, and on the Salween southwest of Baoshan. The occurrence of shallow earthquakes indicates active faults which are at an increased risk of reactivation by RIS due to reservoir filling and drawdown. Given that the naturally occurring conditions for RIS (a large regional stress field acting on existing fault systems *and* seasonal variations in river discharge) characterize much of western China, the risk of RIS from dams in this region becomes that much greater.

Consequently, in addition to the hazard of high natural seismicity in western China, RIS is likely to increase the frequency and perhaps the magnitude of earthquakes in this area. Small RIS events (microquakes) often precede larger RIS events. Microseismic data for newly created reservoirs in western China is generally not available on the USGS website, but is essential for analysis of seismic risk and should be considered in the independent and comprehensive seismic risk assessment recommended in this report.

Finally, because the rate of construction, scale and density of dam building in this area has no global precedent, no one knows if the failure of one large dam will cause the failure of one or more downstream dams. The dams in this area are generally "cascade" dams, where a dam is constructed just upstream from the head of the reservoir of the dam immediately downstream (http://en.wikipedia.org/wiki/File:Yangtze_longitudinal_profile_upstream.JPG; Figure 7). A worrying example of such a cascade of dams in western China can be seen in an area of the Yangtze called the Great Bend in north western Yunnan Province: there, on the north flowing stretch, the Liyuan Dam is under construction, on the south flowing stretch, the Ahai Dam has been completed and its reservoir is filling, while just downstream of Ahai on the south flowing stretch the Jinanqiao and Longkaikou Dams have been completed and their reservoirs filled, followed by the Ludila Dam that is under construction further downstream, where the river begins its eastward flow to the Three Gorges Dam and eventually to Shanghai. These five dams are located in a high to very high seismic hazard zone and near a cluster of large earthquake epicenters north of the city of Lijiang. With dam cascades, undammed stretches of river where energy can be dissipated are not present. So, if one dam fails, the full force of its ensuing tsunami will be directly transmitted to the next dam downstream, and so on, potentially creating a deadly domino effect of collapsing dams. This cascade approach to large dam construction is an experiment that has not been attempted in other areas of the world. Needless to say, a cascade of catastrophic dam failures would almost certainly cause casualties and deaths on a scale never seen before to major downstream population centers, such as Chongqing, and along the valleys of these major rivers. For this reason, populations living downstream of these large dams being constructed in seismically hazardous zones have a right to know the extent of those risks and to stop their expansion.

Conclusion

Given the rapid pace of large dam construction in areas of high natural seismicity in the drainage basins of the Tsangpo, Po, Salween, Mekong, Yangtze, Yalong, Dadu, Min, and Yellow rivers in western China — including in many areas of shallow earthquake focal points, the risk of damage to dams from naturally occurring seismic activity, the probable increase in seismicity due to RIS, and the possibility of the failure of a cascade of dams — a regional study of earthquake hazards and large dams should be conducted to assess the risk of induced earthquakes, and catastrophic failure of one or more dams. This study should be carried out by Chinese seismologists who are independent of the state power bureaucracy and the hydropower industry. Considering that such an extensive program of building cascades of large dams in such a highly seismically active area has no precedent in human history and is thus a very risky experiment, this recommended study must be carried out post haste and disclosed so the public is informed and can hold power sector investors, law makers, and regulators responsible for the financial and human costs of hazardous dam building in western China.

[1] Seismic hazard zones – high, moderate, and low – rate the threat of earthquake shaking and are determined by the focal points and magnitudes of past earthquakes. The epicenter of an earthquake is the

point of the earth's surface directly above the focal point of an earthquake, which is the point of initial rupture. It is a mathematical construct created by drawing a line from the center of the earth to the surface of the earth through the focal point. The epicenter is the point on the earth's surface that is closest to the focal point and represents the point on the earth's surface where maximum shaking occurs for each earthquake.

[2] This data, from the US Geological Survey (USGS/NEIC (PDE) 1973 - 2011 earthquake database at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php), was accessed in April 2011. The USGS earthquake database is updated as seismic events occur.

[3] Dams are said to be in a "cascade" when one dam is constructed just upstream from the head of the reservoir of the next dam downstream.

[4] Reducing the frequency and speed with which reservoir levels fluctuate to service electricity generation, flood control, and downstream water needs may reduce the chances of reservoir induced seismicity and are now being considered by China's dam and river authorities.

[5] Of the 137 dams plotted in Figures 1 and 6, as of 2010, approximately 26 percent have been constructed, 24 percent are under construction, and 50 percent are proposed or are in the planning stage for construction.

[6] This map was prepared by HydroChina based on pre-2004 data and was available on HydroChina's website as of the date of this publication. The status of some dams has changed. For example, Google Earth images dated March 11, 2004 indicate that the Nina Dam (36.022N, 101.267E) on the Yellow River has a full reservoir and is thus completed. However, according to the ziyuan_b map, the Nina dam is under construction.For example, Google Earth images dated March 11, 2004 indicate that the Nina Dam (36.022N, 101.267E) on the Yellow River has a full reservoir and is thus completed. However, according to the ziyuan_b map, the Nina dam is under construction. According to their official website, the HydroChina Corporation, formerly known as the Administration of Water Resources and Hydropower Planning and Design (AWRHPD), acts as a government administrative agency responsible for engineering and construction of the water resources and hydropower projects nationwide. With a history of more than 50 years, HydroChina was established in December 2002 with the approval of China's State Council. According to HydroChina's website, "HydroChina is the chief organization preparing and updating technical specifications, codes and technical standards for China's hydropower and wind power development. HydroChina has prepared and updated the national technical specifications for China's hydropower industry covering the project classification, reconnaissance, planning, land requisition and resettlement, environmental protection engineering, hydraulic structures, construction, cost estimation, mechanical and electrical design, meanwhile, prepared and updated technical standards for wind power projects in aspect of planning, reconnaissance, design as well as operation management, etc. By the end of 2007, HydroChina had completed 160 national and industrial specifications for China's hydropower and wind power which has played an important role in the Chinese hydropower and wind power development.

> "*HydroChina has also undertaken and completed the safety appraisal work for many hydropower projects (including the Three Gorges Project), accounting for 70 percent of the hydropower projects safety appraisal in China.*" [Emphasis added]

[7] For example, see the excellent maps and dams database presented on http://tibetanplateau.blogspot.com..

[8] Since 2008, when the map was first accessed by the author, it is possible that some dams have been cancelled, some completed, and others added to the roster of dams scheduled for construction. For this reason, the analysis used in this study should be applied to an updated list of hydropower dams. Also, because the latitude and longitude coordinates are not available for each dam, their location and their coincidence with seismic data is dependent on the accuracy of the "ziyuan_b" map. To remove any potential mapping errors, the government should release the latitude and longitude coordinates for these dams and the coincidence of dam sites with seismic activity should be re-analyzed.

[9] As of April 2011, the lowest magnitude earthquake in the USGS database in this area was M=3.2. However, because earthquakes smaller than M=5 rarely cause damage, they would have minimal influence on the boundaries of the UN Seismic Hazard Map. For this reason, earthquakes with M<5.0 were deleted from the database used to plot the epicenters in Figures 1 and 6.

[10] See *Reservoir-Induced Earthquakes*, H.K. Gupta, 1992 New York: Elsevier.

[11] Prior to 1973, focal points in this area were unknown to international seismic networks such as the USGS.

[12] The Seismic Hazard Map of China and Mongolia by the Global Seismic Hazard Assessment Program of the United Nations details nine seismic hazard zones: three low, two medium, two high, and two very high. In order to simplify the map, the sub-zones have been consolidated into three categories of hazard: low (PGA 0.0 – PGA 0.8), moderate (PGA 0.8 – PGA 2.4), and high to very high (PGA 2.4 - PGA 5.6) respectively.

[13] The USGS was the first major geological organization to develop an international seismic database. Countries with their own geological survey contribute to it and often use it rather than maintaining their own database. Seismologists with the UN Global Seismic Hazard Assessment Program based their calculations for their World Seismic Hazard Map on USGS data as it is the primary global seismic database. The focal point and magnitude of earthquakes with M>4.9 can be reliably located using the USGS international seismic network prior to 1973. But, due to attenuation, as earthquake magnitudes decrease, their focal points and magnitudes can only be reliably located by local seismic networks that are closer to the focal points. (The reliability of data declines with increasing distance from seismometers, increasing depth of focal point, and decreasing magnitude). Only the Chinese have a complete history of this data for focal points and magnitudes of earthquakes with M<4.9 in parts of western China. China's failure to disclose this data has handicapped the scientific community's ability to evaluate the role of the Zipingpu Dam in the May 12, 2008 Wenchuan earthquake.

[14] The focal point is indirectly indicated via the epicenter location. It is important to note that the various hazard zones delineated by the UN seismologists in western China are also influenced by large earthquake epicenters outside of China: for example, the area around Lhasa in Tibet has relatively few large earthquake epicenters, but if all the large earthquakes in Nepal and India were plotted, it would be obvious why this area is considered a high to very high seismic hazard.

[15] We know from variations in the speed of seismic waves that the earth has a liquid iron core surrounded by a thick mantle of hot, semi-solid siliceous rock that is covered by a cold, rigid crust – imagine a soft boiled egg. The earth's crust is fractured into large plates, which slowly move around over the mantle, causing earthquakes. Where the plates are moving away from each other, new crust is formed, and where they are moving towards each other, such as India's current movement into Asia, old crust is thickened, producing mountain ranges, such as the Himalayas, or it is destroyed by subduction into the mantle and melting, causing volcanic mountain ranges like the Andes. Geologists can measure this movement by dating the age and magnetic orientation of rocks and by using patterns of earthquake focal points and GPS measurements. They use this information to project back in time, creating maps of the earth's continents and oceans as they appeared tens or hundreds of millions of years ago. This is the basis of the theory of plate tectonics.

[16] Approximately 50 million years ago, most of this area was near sea level (much like the Amazon Basin east of the Andes) and now it ranges from 1,000 meters to 8,000 meters above sea level as a result of millions of large earthquakes over this time period. The principle of uniformitarianism states that "the present is the key to the past." For example, if a segment of the earth's crust ruptures and one side is lifted up during a major earthquake (the fault zone), it is reasonable to conclude that the earthquake is responsible for the rupture. So, even in the absence of seismic data going back millions of years, it is reasonable to assume that millions of large earthquakes occurred in this area in order to lift sea floor fossils to the top of Mount Everest. Geologists think the Tibetan Plateau reached its current average elevation of around 5,000 meters about eight million years ago and that this period of uplift and mountain building was accompanied by millions of large earthquakes. Prior to this uplift, the Tsangpo and Po (the Po is a large tributary of the Tsangpo), Salween, Mekong, and Yangtze were probably headwater tributaries of the Red River. These drainages slowly changed to their current configuration during this period of uplift and mountain building, which is the cause of the hundreds of large earthquakes in the past 26 years that were used to determine the seismic hazard zones. (See "Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns" Clark et al., 2004, Tectonics, Vol. 23 or the abstract at http://adsabs.harvard.edu/abs/2004Tecto..23.1006C.

[17] Nearly all major dams in developed countries were constructed prior to the creation of seismic hazard maps.

[18] "Least competent" means less able to withstand high stress. The crest of a dam is most susceptible to being damaged by a tsunami caused by an earthquake-generated landslide into the reservoir.

[19] See photos of the damage at (http://journal.probeinternational.org/2010/05/22/dams-damaged-in-yushu-earthquake/).

APPENDIX A: TABLES

Table 1 – Summary of ziyuan_b dam database for selected rivers in western China

River	Number of dams	Total MW (megawatts)	% of total MW
Dadu*	24	24,310	10
Mekong	18	31,175	13
Min*	3	1,540	1
Po	9	6,892	3
Salween	27	29,380	12
Tsangpo**	4	41,000	17
Yalong	16	27,510	11
Yangtze***	20	67,102	27
Yellow****	16	19,356	8
Totals	**137**	**248 GW (gigawatts)*******	**100**

* Only dams upstream from Leshan. Includes the Zipingpu Dam west of Chengdu, which came close to failing during the May 12, 2008 Wenchuan earthquake (M=7.9).

** Includes a tunnel beneath a 7,782 m peak with a total drop of 1988 m, the largest hydropower facility ever planned: 39 GW, nearly twice the size of the world's largest (Three Gorges Dam, 22.5 GW).

*** Only dams west of Yibin (the confluence of the Min with the Yangtze). Includes two tunnels with a total drop of more than 1,300 m and a total capacity of 24.6 GW.

**** Only dams west of Lanzhou.

***** This is about 11 times greater than the capacity of Three Gorges Dam, which itself produces more hydropower than the fifteen large dams that the US Bureau of Reclamation manages in the western US.

Table 2 – Summary of U.S. Geological Survey (USGS) earthquake database, 1973 – 2011[1] for the area shown on Figures 1 and 6.

Magnitude (M) range	Number of earthquakes within the M range	Average focal point depth (km)*
5.0 – 6.0	333	24
6.1 – 7.0	30	17
7.1 – 8.0	3	23
Totals	**366**	**23**

* Focal point depth is the depth below the earth's surface to point of rupture. There is no particular significance to the variation in depth of focal points here because of the limited size of the database. However, in general the great majority of them are relatively shallow.

[1] Prior to 1973, global seismic monitoring and data collection was less extensive and coordinated. After 1973, the U.S. Geological Survey increased its program of collaboration with other geological researchers at universities and with national bodies in other countries, including China. This had the effect of greatly increasing available databases of seismic activity around the world, all of which are now consolidated in the USGS database. Data collected prior to 1973 also did not include the depth of earthquake focal points, and for many remote areas of the world, such as western China, the latitude and longitude of each earthquake epicenter and its magnitude was estimated.

Table 3 – Percentage of total dams (based on the 137 dams in the ziyuan_b map) in each seismic hazard zone for each river

River	Percentage of dams in the high to very high seismic hazard zones %	Percentage of dams in the moderate seismic hazard zones %	Percentage of dams in the low seismic hazard zones %
Dadu	10.8	6.7	0
Mekong	3.6	9.5	0
Min	0	2.2	0
Po	5.8	0.7	0
Salween	3.6	16.2	0
Tsangpo	2.9	0	0
Yalong	9.5	2.2	0
Yangtze	11.6	2.9	0
Yellow	0	10.2	2
Total Percent	**48.1**	**50.5**	**1.4**

Table 4 – Percentage of total megawatt (MW) capacity in each seismic hazard zone for each river based on the 137 dams in the ziyuan_b map

River	**High to Very High**	**Moderate**	**Low**
Dadu	6.3	2.8	0
Mekong	3.6	8.7	0
Min	0.4	0.6	0
Po	2.5	0	0
Salween	3.9	9.7	0
Tsangpo	17.3	0	0
Yalong	11.5	2	0
Yangtze	21.7	1.2	0
Yellow	0	0	0.3
Total Percent	**67.2**	**32.5**	**0.3**

Table 5 – Estimated number of dams completed, under construction and proposed on each river as of December 2011 in this region.

River	Constructed*	Under Construction *	Proposed*	Total
Dadu	5	11	8	24
Mekong	4	6	8	18
Min	6	1	-4	3
Po	0	0	9	9
Salween	2	2	23	27
Tsangpo	1	1	2	4
Yalong	3	4	9	16
Yangtze	1	4	20	15
Yellow	14	3	-1	16
Total	**35**	**33**	**69**	**137**
PERCENTAGE	**25.5**	**24.1**	**50.4**	**100**

* The total number of dams constructed and under construction is based on an unpublished 2011 database prepared by International Rivers (www.international rivers.org) and confirmed by identifying listed dams on Google Earth satellite images. The total of proposed dams for each river was calculated by subtracting the sum of constructed and under-construction dams from the total number of dams shown on the ziyuan_b map. Negative numbers for proposed dams indicate that the ziyuan_b map did not include all dams currently visible on Google Earth. The primary purpose of this Table is that it provides a way to calculate the rate of dam construction (see Discussion).

Table 6: Incidences of RIS resulting in damage to dams and other structures 1937 – 1981*

Name	Country	Year	Magnitude
Koyna (dam damaged)	India	1967	6.3
Kariba (dam damaged)	Zimbabwe	1963	6.2
Kremasa (dam damaged)	Greece	1966	6.2
Xinfengjiang (dam damaged)	China	1962	6.1
Oroville**(nearby structures damaged)	USA	1975	5.7
Marathon (nearby structures damaged)	Greece	1938	5.7
Aswan (nearby structures damaged)	Egypt	1981	5.6
Hoover (nearby structures damaged)	USA	1939	5
Eucombene (nearby structures damaged)	Australia	1959	5
Benmore (nearby structures damaged)	New Zealand	1966	5

* Source: *Reservoir-Induced Earthquakes*, H.K. Gupta, 1992 New York: Elsevier.

** This event, and the proximity of the Oroville Dam on the Feather River in northern California to the proposed Auburn Dam on the American River upstream from the capital city of Sacramento, resulted in a decision to abandon construction of the Auburn Dam in 1978.

APPENDIX B: FIGURES

Figure 1 – Seismic hazard map showing dams and major earthquake epicenters in western China

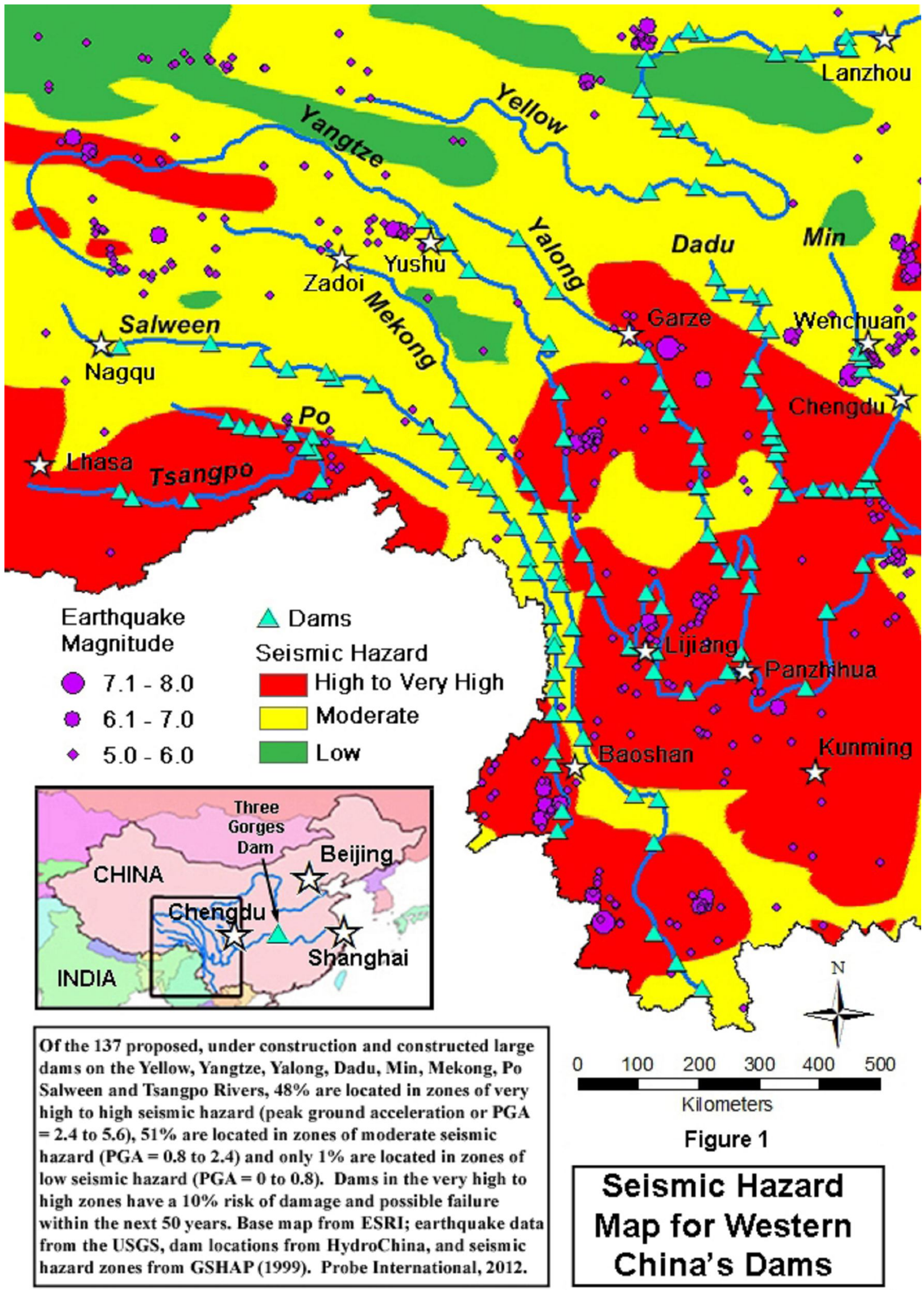


Figure 2 – The "ziyuan_b" map obtained from Hydrochina.
http://www.hydrochina.com.cn/zgsd/images/ziyuan_b.gif

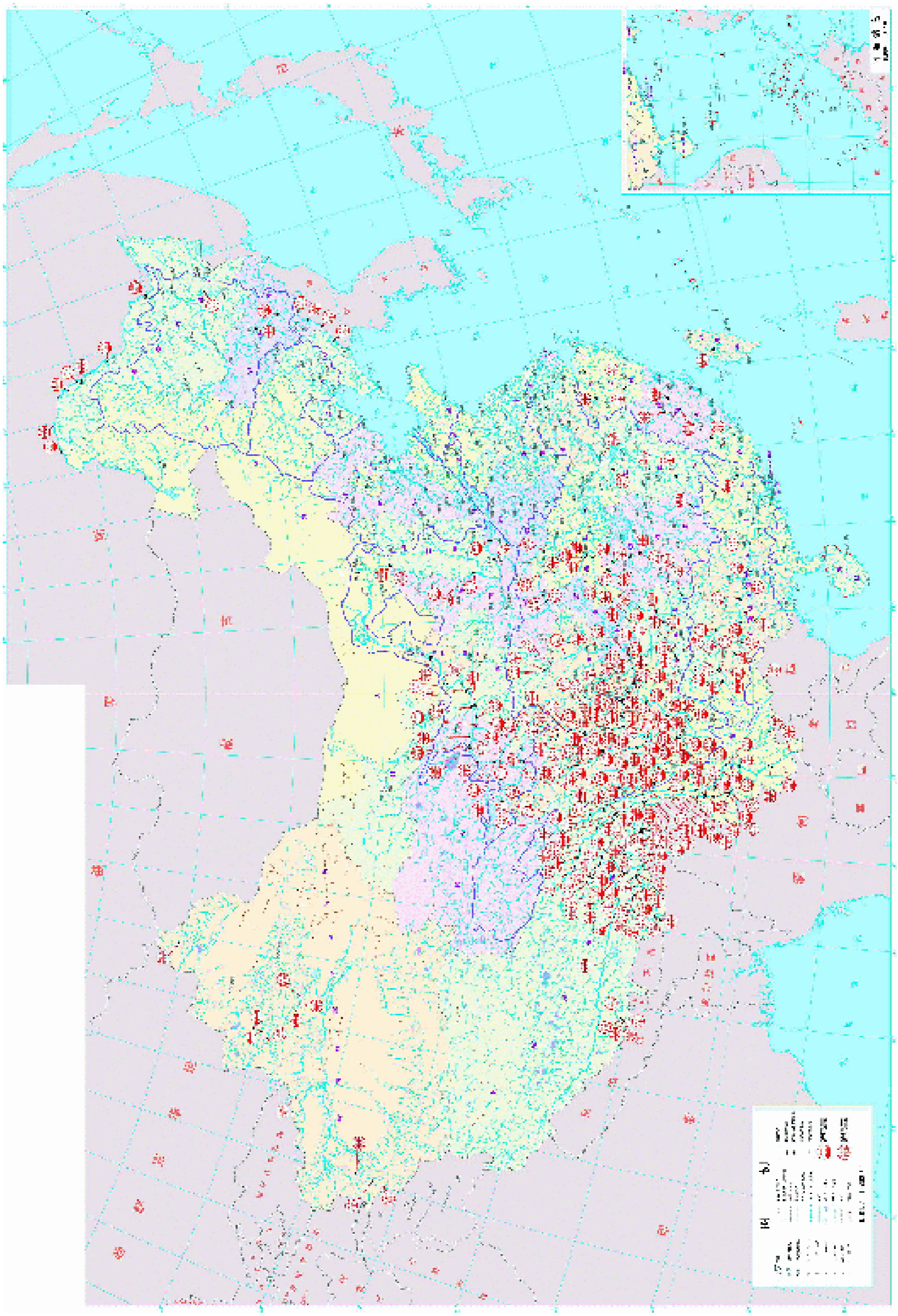


Figure 3 - Geological Map of Nujiang, Lancang and Jinsha Rivers Area, Ministry of Geology and Mineral Resources, Chinese Academy of Sciences, 1980.

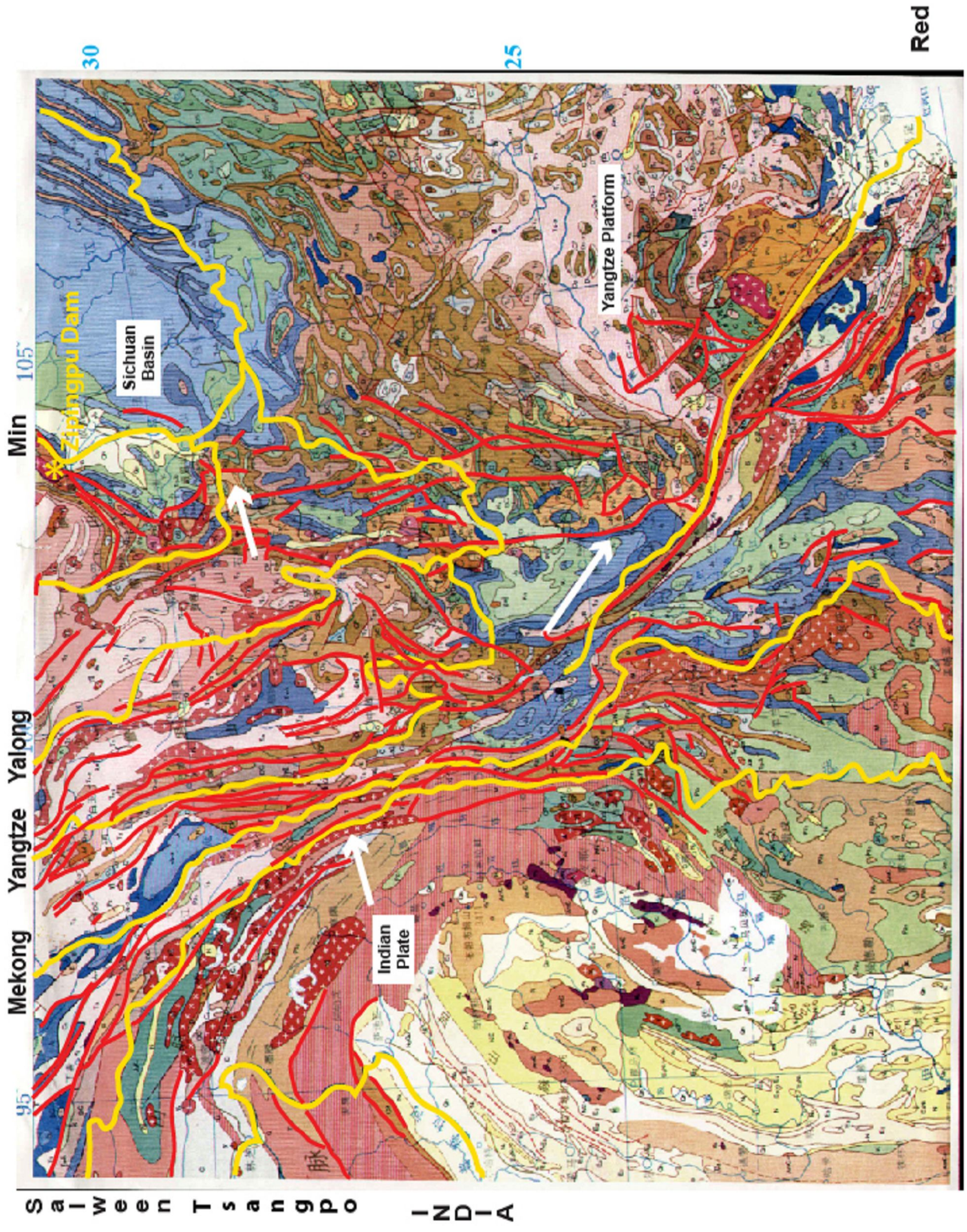


Figure 4 - [Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements, Gan et. al., 2007]

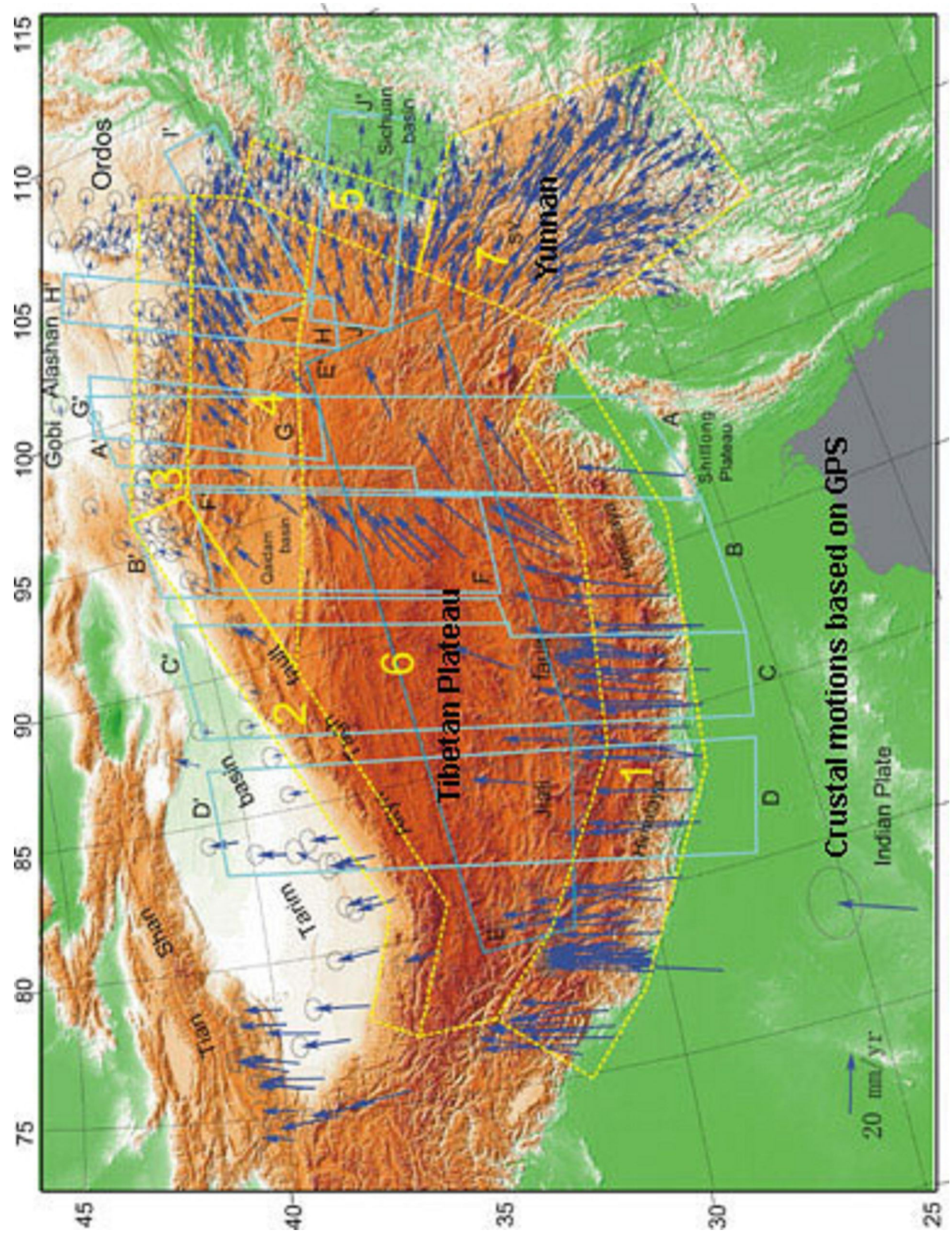


Figure 5 – Seasonal variation in Yangtze flow rate at Three Gorges (originally from Wikipedia).
http://en.wikipedia.org/wiki/Three_gorges_dam

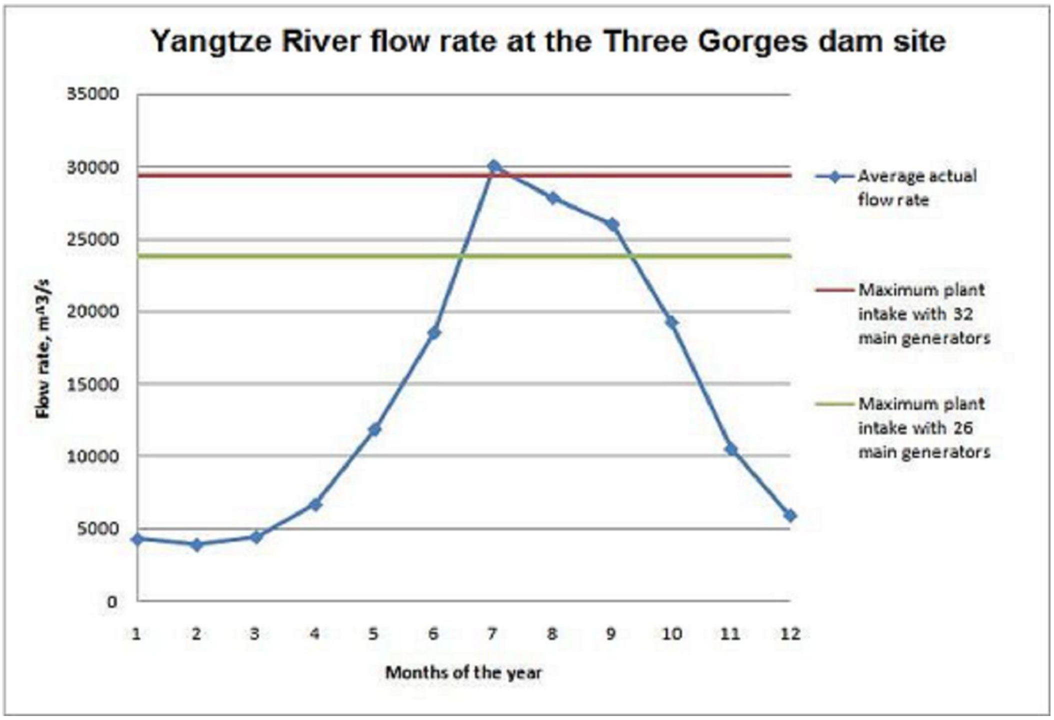
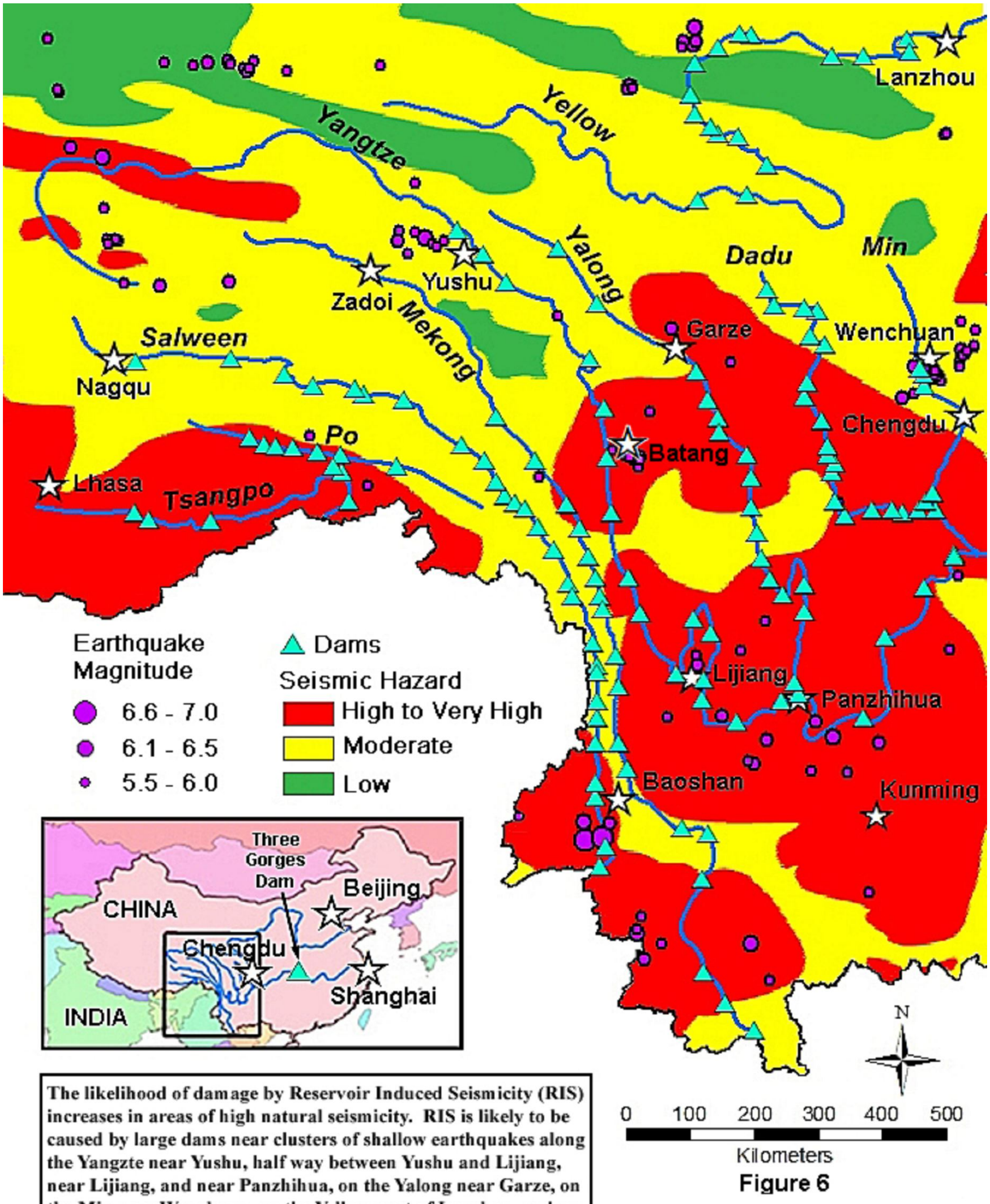


Figure 6 – Proximity of large dams to seismic hazard zones and shallow (< 10 km) earthquakes in western China.



The likelihood of damage by Reservoir Induced Seismicity (RIS) increases in areas of high natural seismicity. RIS is likely to be caused by large dams near clusters of shallow earthquakes along the Yangzte near Yushu, half way between Yushu and Lijiang, near Lijiang, and near Panzhihua, on the Yalong near Garze, on the Min near Wenchuan, on the Yellow west of Lanzhou, and on the Salween near the Myanmar border. This risk is higher for dams in zones of high to very high seismic hazard. Base map from ESRI; earthquake data from the USGS, dam locations from HydroChina, and the seismic hazard zones from GSHAP (1999). Probe International, 2012.

Proximity of Large Dams in Western China to Seismic Hazard Zones and Earthquakes < 10 km deep

Figure 7 – Cascade dams on the Yangtze River (Wikipedia).
http://en.wikipedia.org/wiki/Three_gorges_dam