Earthquake Hazards and Large Dams in Western China

A Probe International Study

By

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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 and seismic hazard zones[1] for dams that are built, 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 48.2 percent are located in zones of high to very high seismic hazard. The remaining 50.4 percent are located in zones of moderate seismic hazard, and only 1.4 percent are located in zones of low seismic hazard (see Table 3). With respect to power generation capacity, 67.2 percent of the combined total megawatt capacity is located in high to very high seismic hazard zones, 32.5 percent in zones of moderate seismic hazard, and only 0.3 percent in zones of low seismic hazard (see Table 4).

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.

Moreover, the rapid rate of construction and the location of dams around clusters of M>4.9 earthquake epicenters (of events between 1973 and 2011[2]) is significant cause for concern. In less than a decade there has been a 267 percent increase in dams built and dams under construction. The risk of earthquake damage caused by the region's high natural seismicity is compounded by the risk of Reservoir-Induced Seismicity (RIS),[3] 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.[4]

The purpose of this report is to highlight for the Chinese government the urgent need for an independent, comprehensive, and expert seismic risk assessment of the extensive dam-building program underway in western China. In order to provide the best assessment of the seismic risk hazard of China's dam-building program, the recommended study should be prepared using mapping software similar to that used in this report but with an up-to-date list of dams with precise latitude and longitude locations, and size of dams situated within the known seismic hazard zones and in relation to historical temblors of more than M4.9.

The proposed study would inform risk assessments and investment decisions, highlight the need for improved safety standards in dam construction and operation, as well as better emergency preparedness, and lead to the cancellation of dams which pose an unacceptable risk to public safety.[5] The proposed study must also be disclosed to China's citizens, press, power companies, financial institutions, and law-makers to ensure an informed public debate is undertaken on the risks of dam-building, as well as to ensure liability for hazards and damages is properly assigned, and safety standards and emergency preparedness procedures are widely disseminated and debated. Due to the rapid rate of dam construction in China, this proposed study should be completed as soon as possible.

The purpose of this report is to highlight for the Chinese government the urgent need for an independent, comprehensive, and expert seismic risk assessment of the extensive dam-building program underway in western China.

The database of dams built, under construction, and planned for China's rivers, used by this study, comes from a map prepared by HydroChina prior to 2004, with data confirmed by more recent surveys, as well as Google Earth satellite images. Based on this review, it appears that about half of these dams have not yet been built, but that the pace of construction is rapid.[6] This makes a seismic risk hazard assessment of dams in western China all the more urgent.

Introduction

Figure 1 shows the locations of major dams either built, under construction, or proposed for 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 published by HydroChina and reproduced in Figure 2.[7] There are more detailed maps on other websites which show additional dams,[8] 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 in the "ziyuan_b" map, on the rivers listed above, are included in this analysis (see Table 1).[9]

This proposed study must also be disclosed to China's citizens, press, power companies, financial institutions, and law-makers to ensure an informed public debate.

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.[10] M>4.9 was selected as the minimum because earthquakes of magnitude 5.0 or greater have been known to cause damage to dams and to other structures (see Table 6).[11]

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. 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.[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).

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 an unpublished database of China's dams by International Rivers 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 either built, under construction, or planned for each of these rivers, in all likelihood, this database is incomplete and underestimates the number of dams on these rivers. Moreover, the status of the 137 dams has changed since 2004 (when the ziyuan_b map is believed to have been finished): Table 5 lists 66 dams that have been built or are under construction for each river in this region as of 2011. These 66 dams represent 48 percent of the 137 dams shown on the ziyuan_b map which, in 2004, recorded only 12 percent of the dams as built or under construction. This rapid rate of dam construction 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, as well as the magnitudes and epicenters of earthquakes in western China, has allowed us to produce seismic hazard maps for dams in western China: see Figures 1 and 5, and the data sets found in Tables 1- 4. These figures and tables reveal several disturbing patterns.

Figure 1 and Table 3 indicate that 48.2 percent of all dams built, under construction, or planned for construction are located in zones of high to very high seismic hazard, 50.4 percent are located in zones of moderate seismic hazard, and only 1.4 percent are located in zones of low seismic hazard.

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

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

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Because the damage caused by earthquakes increases with proximity to the epicenter, and increases as focal point depth decreases (i.e. the seismic waves that cause vertical and horizontal ground shaking attenuate with distance in all directions), the location of large dams near clusters of earthquake epicenters with M>4.9 (Figure 1), and especially around clusters of earthquake epicenters with focal points <10 km deep and magnitudes of 4.9 or greater (Figure 5), is cause for grave concern.[14]

The location of large dams near clusters of earthquake epicenters with M>4.9, and especially around clusters of earthquake epicenters with focal points<10 km deep and magnitudes of 4.9 or greater, is cause for grave concern.

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 shows the high number of active faults in this area (with faults and rivers highlighted). Figure 4 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 measures 0.8 to 2.4 m/s^2, and the low zone PGA measures 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 percent probability of being exceeded within 50 years of 1999 (i.e. 2049).[16]

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 entire region of western China, shown in Figure 4, would be classified as a high to very high seismic hazard zone.[17]

In the area of western China under discussion, 18 of the 137 dams built on the aforementioned nine rivers were constructed or under construction prior to 2004. Based on Table 5, since then an additional 48 dams have been constructed or are under construction, an increase of 267 percent in less than a decade. If all 137 dams on the ziyuan_b map are to be completed, an additional 71 dams will be built 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.

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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. It is interesting to note that nearly all major dams in developed countries were constructed prior to the creation of the seismic hazard maps. In 2005, to assess the effects of earthquakes on existing dams, the US Federal Emergency Management Agency (FEMA) published "Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams"[18] and, 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".[19]

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 and inherent resonant frequencies of dams are different from the density of the ground upon which they rest and from the water in their reservoirs. Consequently, the vibrational patterns of the various elements can interact in destructive ways during an earthquake. 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.[20] Additional information is available from the US Association of Dam Safety Officials.

Examples of recent seismic damage to dams in China include the 2008 M7.9 Wenchuan earthquake about 100km (60 miles) northwest of Chengdu and the 2010 M6.9 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, located on the Min River. This earthquake caused cracks in the dam structure and collapsed walls at the power plant. The generators also 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-meter 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.[21]

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Another risk factor that must be considered is reservoir-induced seismicity (RIS). RIS occurs when two major factors are present: a regional stress field acting on an existing fault system and seasonal fluctuations of reservoir levels.[22] 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 M7.9 earthquake.[23] H.K. Gupta identifies four cases in which dams caused M6.1 to M6.3 RIS earthquakes that were, in turn, damaged by the quakes, as well as six dams that caused M5.0 to M5.7 earthquakes that resulted in damage to nearby structures (see Table 6). For example, the Xinfengjiang Dam in southeast China (Latitude 23.73N, Longitude 114.65E) was seriously damaged in 1962 by the M6.1 earthquake that it triggered.[24]

The basic premise of RIS is that a full reservoir lubricates active faults by increasing pore pressure at focal point depths, and that subsequent reservoir water drawdown reduces the stabilizing force of friction caused by the mass of the water in 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

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. For example, the average August discharge of the Yangtze below the lowest dam included in this report is nine times greater than the average discharge in January at the same location.[25]

Most RIS-generated earthquakes have a focal point less than 10 km deep. Figure 5, which overlays the maps of dam locations, seismic hazard zones, and the locations of earthquake epicenters with focal point depths less than 10 km 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.

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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 are generally not available on the USGS website, but are 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 located 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.[26] A worrying example can be seen in an area of the Yangtze called the Great Bend in northwestern 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, also on the south flowing stretch, the Jinanqiao and Longkaikou Dams are completed and their reservoirs are filled. The Ludila Dam, which is still under construction, is located 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.

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A major problem with dam cascades is that there are no undammed stretches of river where the energy of a tsunami can dissipate in the event of catastrophic dam failure. 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. A cascade of catastrophic dam failures would almost certainly cause an unprecedented number of casualties and deaths in major downstream population centers, such as Chengdu, and along these major river valleys. For this reason, people living downstream of large dams 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 the drainage basins of the Tsangpo, Po, Salween, Mekong, Yangtze, Yalong, Dadu, Min, and Yellow Rivers in western China – areas of high natural seismicity with many areas of shallow earthquake focal points – there is a high risk of damage to dams and causalities among populations downstream from naturally occurring and reservoir-induced seismicity. A regional scientific study of earthquake hazards and large dams should be conducted to assess this risk and the potential for catastrophic failure of one or more dams. This study should be carried out by seismologists who are independent of the Chinese state power bureaucracy and the hydropower industry. As there is no precedent in human history for the construction of over 130 large dams in such a highly seismic area – no other program to build cascades of large dams in areas of high seismicity exists to draw upon – the China example stands alone as a very risky experiment. Therefore, this recommended study must be carried out and disclosed to the public post-haste, so the people of China can hold the country's power-sector investors, law-makers, and regulators to account for the financial and human costs of hazardous dam building in western China.

The potential for catastrophic failure of one or more dams must be assessed so the people of China can hold the country's power-sector investors, law-makers, and regulators to account for the costs of hazardous dam building in western China.

Endnotes

[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] US Geological Survey, *Earthquake Database*,<http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php>, (April 2011), 1979-2011.

[3] A type of earthquake that is triggered by certain geophysical changes associated with reservoir impoundment.

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

[5] 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. This is now being considered by China's dam and river authorities.

[6] Of the 137 dams plotted in Figures 1 and 5, as of 2011, approximately 26 percent have been built, 23 percent are under construction, and 51 percent are proposed or are in the planning stage for construction.

[7] 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. 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 the engineering and construction of 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."

[8] For example, see the map and dam database for each river presented on <http://tibetanplateau.blogspot.com/>.

[9] 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.

[10] As of April 2011, the lowest magnitude earthquake in the USGS database in this area was M3.2. However, because earthquakes smaller than M5 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 5.

[11] H.K. Gupta, *Reservoir-Induced Earthquakes* (New York: Elsevier, 1992).

[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 after 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] 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 into the seismic hazard map prepared by the UN's Global Seismic Hazard Assessment Program. 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 M7.9, and Yushu in 2010, at M6.9), both of which occurred in areas assessed in 1999 as being of 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.

[17] 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.

[18] Federal Emergency Management Agency (FEMA), *Federal Guidelines for Dam Safety: Earthquakes Analyses and Design of Dams*, <http://www.damsafety.org/media/Documents/PDF/fema-65.pdf>, 2005.

[19] I.M. Idriss and Ralph J. Archuleta, "Evaluation of Earthquake Ground Motions," <http://www.ferc.gov/industries/hydropower/safety/guidelines/eng-guide/chap13-draft.pdf>, 2007.

[20] "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.

[21] See Dams Damaged in Yushu Earthquake for photos of the damage.

[22] H.K. Gupta, *Reservoir-Induced Earthquakes* (New York: Elsevier, 1992).

[23] Fan Xiao, "Chinese Geologist Says Zipingpu Dam Reservoir May Have Triggered China's Deadly Quake, Calls for Investigation," <http://journal.probeinternational.org/2009/01/26/chinese-geologist-says-zipingpu-dam-reservoir-may-have-triggered-chinas-deadly-quake-calls-investigation/>, 2009.

[24] Linyue Chen and Pradeep Talwani, "Reservoir-induced Seismicity in China," < http://www.seis.sc.edu/projects/SCSN/history/Publications/pageoph98/pageoph98.pdf>, 1998.

[25] M. Sugawara and E. Ozaki, "Runoff Analysis of the Chang Jiang (the Yangtze River)," <http://iahs.info/hsj/360/hysj_36_02_0135.pdf>, 1991, p. 137.

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APPENDIX A: TABLES

A note on the Tables

The analysis of the seismic risk of dams located in western China, on the nine rivers cited, is based on dams located on HHydroChina's ziyuan_bH map, and confirmed and updated to the extent possible, by other databases, including an unpublished list prepared by International Rivers, maps posted on HTibetanBlogH, and finally by HGoogle EarthH images last accessed in March 2012.

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	9.8
Mekong	18	31,175	12.6
Min*	3	1,540	0.6
Po	9	6,892	2.8
Salween	27	29,380	11.8
Tsangpo**	4	41,000	16.5
Yalong	16	27,510	11.1
Yangtze***	20	67,102	27.0
Yellow****	16	19,356	7.8
Total	**137**	**248,265**^	**100**

* Dams upstream from Leshan, including the Zipingpu Dam west of Chengdu, which came close to failing during the May 12, 2008 Wenchuan earthquake (M7.9).

** 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).

*** Dams west of Yibin (the confluence of the Min with the Yangtze), including 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.

^ The total 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 5

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
Total	**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. 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 greatly increased availability of 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 were estimated.

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

River	Dams in the high to very high seismic hazard zones (%)	Dams in the moderate seismic hazard zones (%)	Dams in the low seismic hazard zones (%)
Dadu	10.9	6.6	0
Mekong	3.7	9.5	0
Min	0	2.2	0
Po	5.8	0.7	0
Salween	3.7	16.1	0
Tsangpo	2.9	0	0
Yalong	9.5	2.2	0
Yangtze	11.7	2.9	0
Yellow	0	10.2	1.4
Total Percent	**48.2**	**50.4**	**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	7.5	0.3
Total Percent	**67.2**	**32.5**	**0.3**

Table 5 – Estimated number of dams completed and under construction before 2004, as of 2011, and the percentage increase.

River	Pre 2004*	2011**	Percent Increase (%)
Dadu	3	16	433
Mekong	3	10	233
Min	2	7	250
Po	0	0	0
Salween	2	2	0
Tsangpo	1	2	100
Yalong	1	7	600
Yangtze	1	5	400
Yellow	5	17	240
Total	**18**	**66**	**267**

* From HydroChina's ziyuan_b map

** From International Rivers' database and confirmed by Google Earth images

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

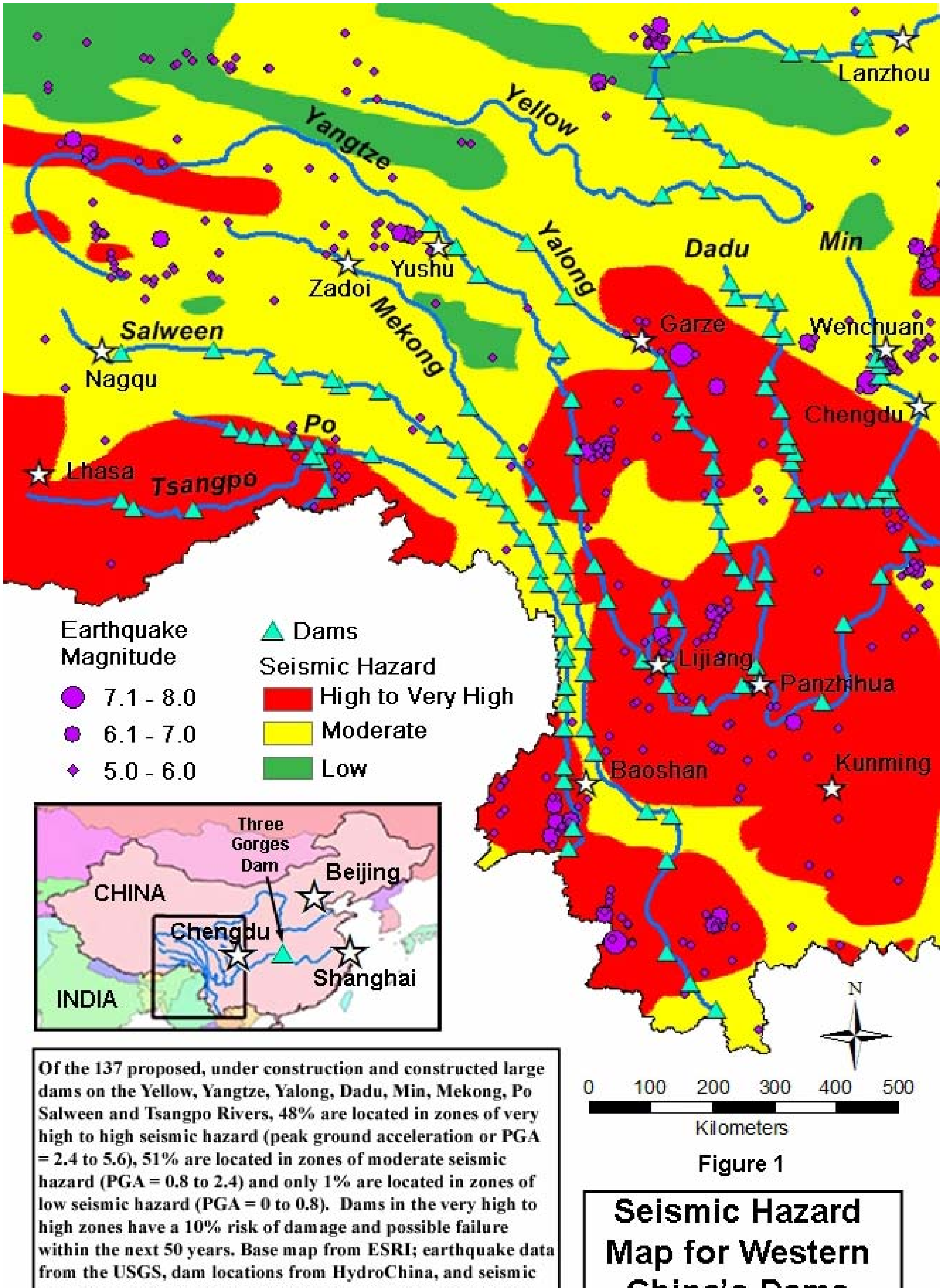
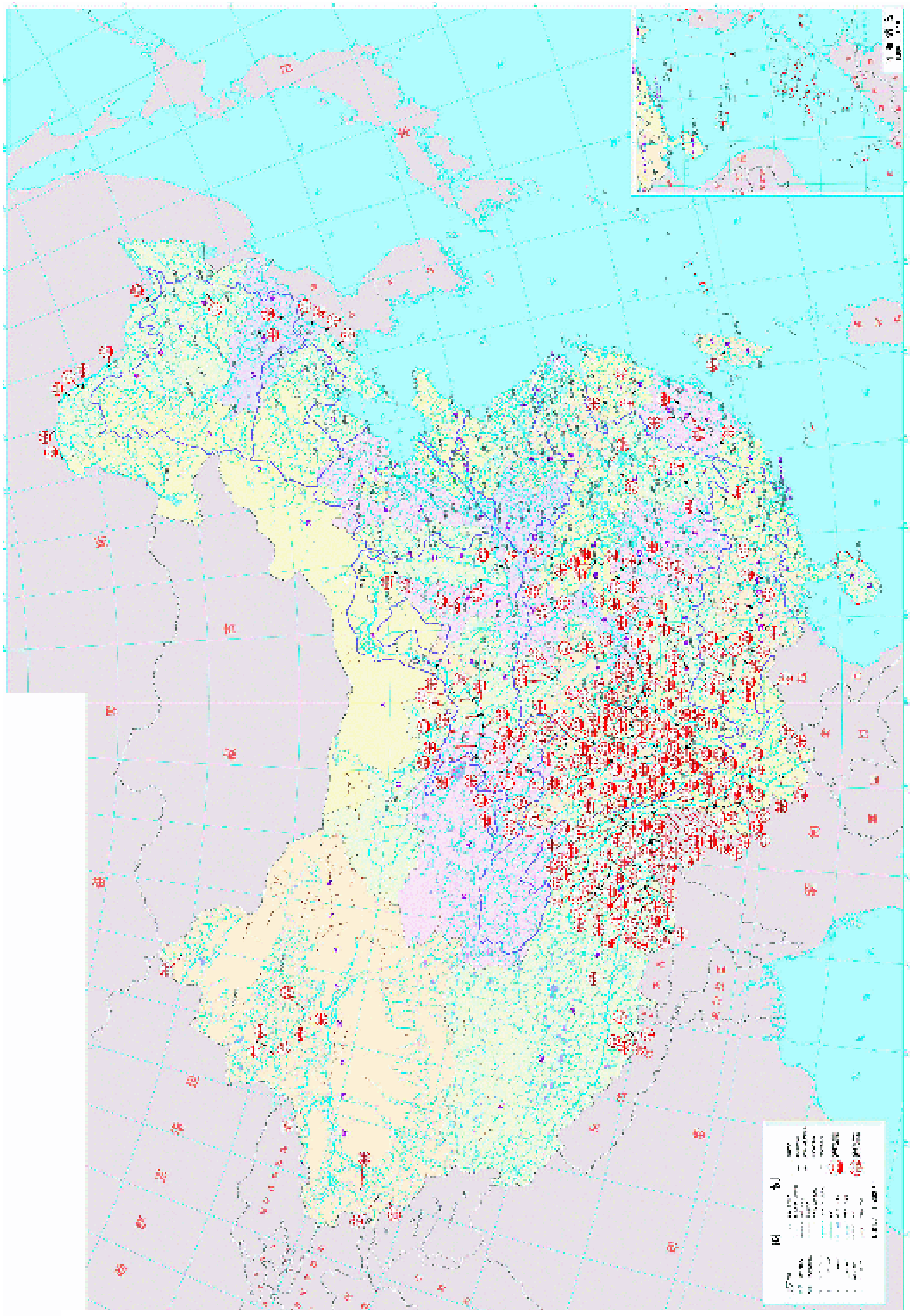
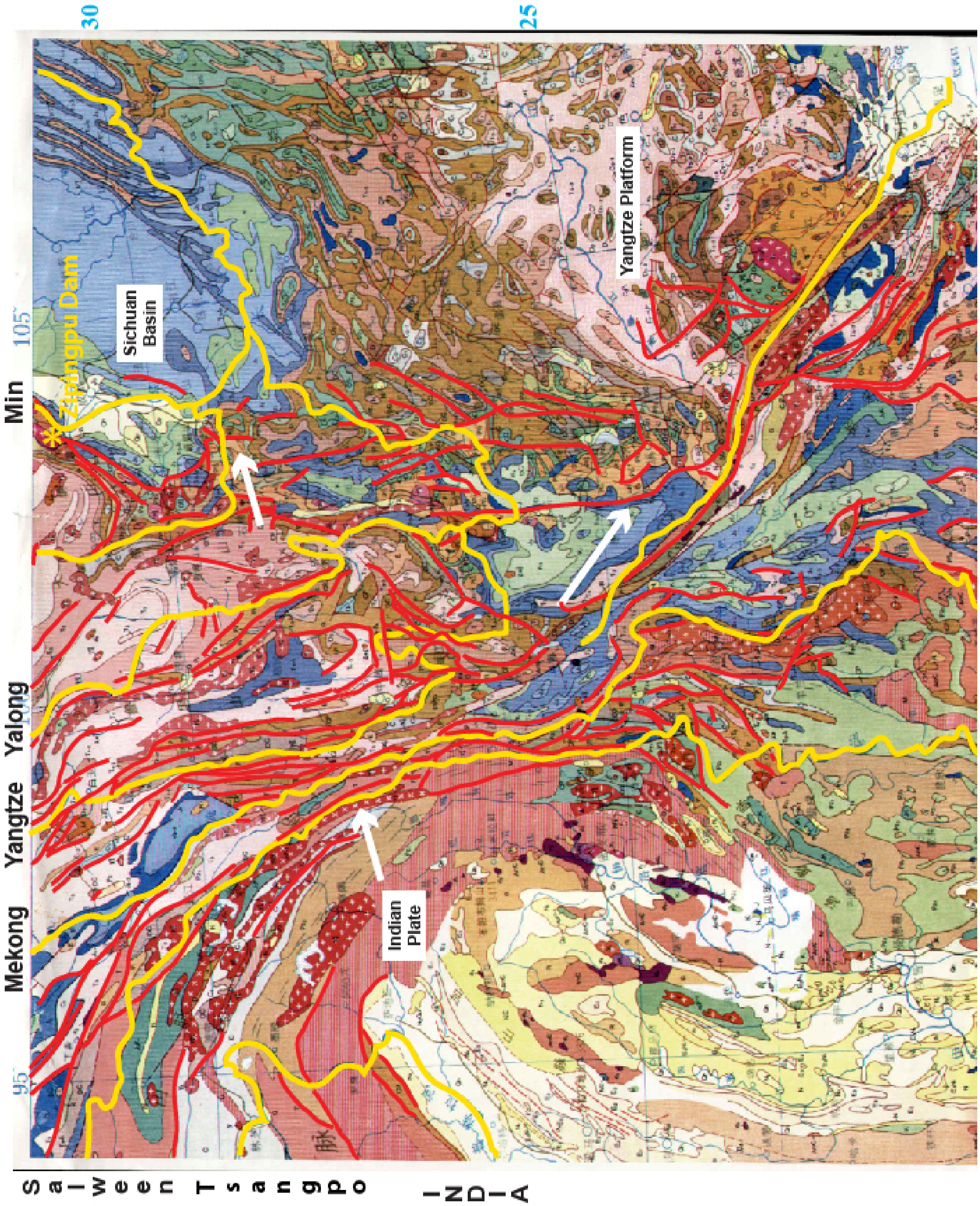


Figure 2 – Map of major dams in China (map "ziyuan_b")



Source: HydroChina, <Hhttp://www.hydrochina.com.cn/zgsd/images/ziyuan_b.gifH>
On the full scale map, the key and text within the circles identifying each dam are legible. Information includes the name of the dam, size (megawatts), and status prior to 2004 (built, under construction, or proposed).

Figure 3 - Geological map of Nujiang, Lancang, and Jinsha river area (rivers in yellow, faults in red)



Source: 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

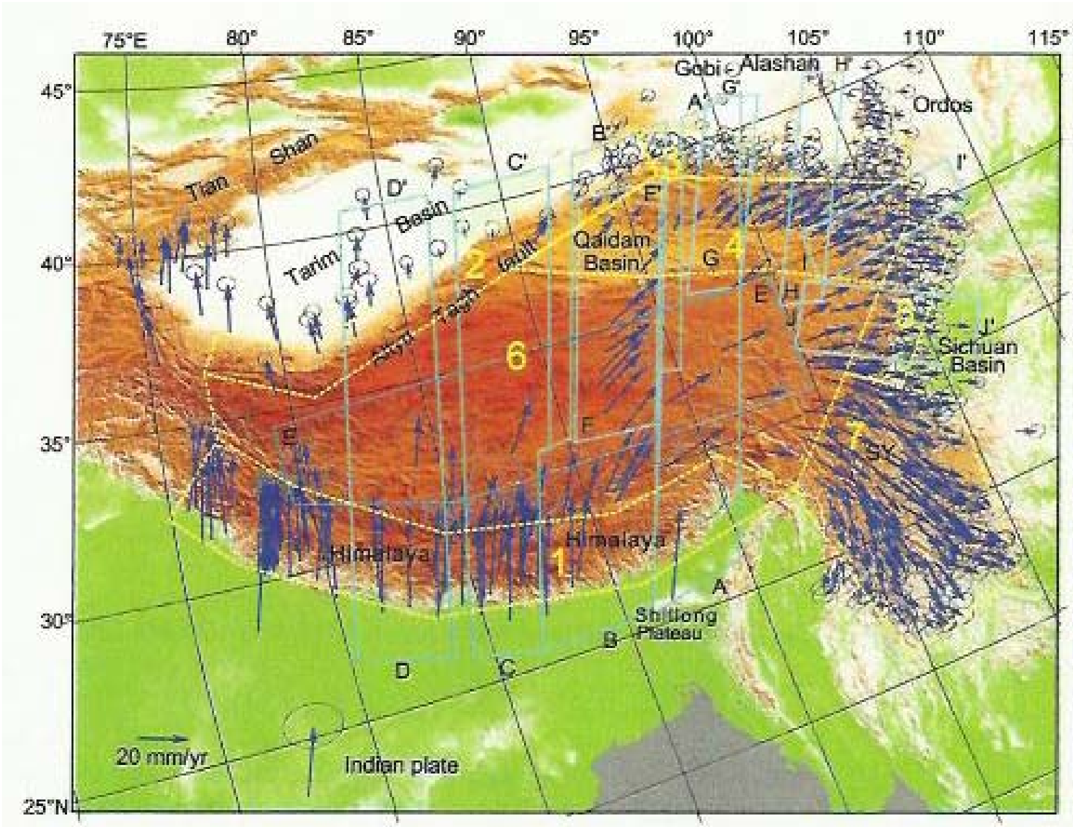


Figure 1. Global positioning system (GPS) velocities (mm/yr) in and around Tibetan Plateau with respect to stable Eurasia, plotted on shaded relief map using oblique Mercator projection. Ellipses denote 1σ errors. Blue polygons show locations of GPS velocity profiles in Figures 3 and DR1 (see footnote 1). Dashed yellow polygons show regions that we used to calculate dilatational strain rates. Yellow numbers 1–7 represent regions of Himalaya, Altyn Tagh, Qilian Shan, Qaidam Basin, Longmen Shan, Tibet, and Sichuan and Yunnan, respectively.

Source: Zhang et.al., "Continuous deformation of the Tibetan Plateau from global positioning system data". *Geology,* Vol.. 32 (9), 2004 p 810.

Figure 5 - Proximity of large dams to seismic hazard zones and shallow (< 10 km) earthquakes in western China