STATE of KNOWLEDGE

The Effects of Hydropower Dams on the Hydrology of the Mekong Basin

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Key Messages

This State of Knowledge paper sets out to summarize existing research on how hydropower development will affect the hydrology of the Mekong River. Hydropower development is expected to modify the hydrology of the Mekong River and many of its tributaries by reducing and delaying wet season flows, and increasing dry season flows. The magnitude of these changes varies by location within the Mekong Basin, and is uncertain because there are differences among hydrological models and dam development scenarios.

Increased dry season flows downstream of dams will provide more opportunities for irrigation, navigation and hydropower production. Conversely, many ecosystems and livelihoods adapted to natural flow extremes may be affected. Increased dry season flows will also limit opportunities for riverbank gardening. While hydropower reservoir storage is expected to reduce wet season flows, its effects on flood peaks are less certain partly because it is difficult to predict the effects of the emergency operating rules that dam managers use to prevent flood damage to dams.

Along Mekong tributaries, the hydrological effects of hydropower development will vary, depending on whether a dam produces energy on-site or is used to divert water to an off-stream location.

Other impacts of hydropower include increases in the variation of daily river flows in the dry season due to the irregular releases from reservoirs made in response to fluctuating electricity demands. In contrast, during the wet season, reservoir storage tends to reduce the variation in natural flows downstream.

Overall, the projected hydrological impacts of hydropower will be stronger than those of climate change. Some studies suggest, however, that increases in irrigation withdrawals will nearly compensate for the dam-induced increases in dry season flow within a few decades.

The hydrological impacts of land cover change taking place at the same time as hydropower development have only been demonstrated in tributary basins. The difficulty of acquiring reliable long-term land cover datasets makes it hard to determine the effects of land cover change on the hydrology of the entire basin.

Most studies on the hydrological impacts of hydropower development in the Mekong attempt to model potential impacts. Far fewer studies have examined the observable impacts of hydropower development, mainly because (a) most dams have been recently constructed and, as a result, lack post-dam hydrological records of sufficient length; and (b) many sites have insufficient pre-dam records for establishing a basis for comparison.

More studies on ecological and livelihood responses to hydrological changes in the Mekong basin are needed to better understand the implications of hydropower development to ecosystems and livelihoods, and to mitigate their negative long-term impacts.

How does hydropower affect river flow?

Hydrology is the study of the movement of water in the natural environment over time. The volume of water that moves between two places through a particular conduit, such as a river channel, over a given time period is commonly known as the flow or discharge. Estimating the flow helps water resource managers to judge how much water may be available for different uses, including in-stream uses, such the water needed by aquatic ecosystems, and power generation; as well as off-stream ones, such as irrigation and domestic water supply. Changes in flow also cause water level changes, which have direct implications for agricultural production, navigation, infrastructure, human safety and ecosystems.

The way hydropower dams affect river flows depends on their storage capacity and operation. Dams with storage reservoirs that are large relative to the amount of water that they receive reduce seasonal river flow variations downstream (for example, by storing water during the wet season, so that energy can be generated during the dry season). In the Mekong, reservoir dams have a much greater impact on seasonal flows than they do on flow changes across years. The wet, or rainy, season is often considered to run from June to November while the dry season lasts from December to May, although definitions of these two seasons may vary slightly among studies.

When natural river flow is sufficient to generate energy all year round, very little storage capacity is required. Such dams are called run-of-river dams, which typically store no more than a few days of the average flow. (Note that strict definitions of run-of-river dams may vary and that the run-of-river classification of some Lower Mekong mainstream dams has been challenged (Baran et al., 2011). However, in this review, we loosely use the term to describe dams whose reservoirs cannot store more than a few days of average flow.)

In general, the more water that is stored behind a dam, the more it will affect a river's flows. How dam operators release water through the dam depends on when and how much electricity is needed. This can change during the day (the demand tends to be lower at night), and during the week (the demand tends to be lower during the weekend). This strategy, called 'hydropeaking', helps maximize power production and economic profits and is used by both reservoir and run-of-river dam operators. Many of the large run-of-river dams proposed on the Mekong mainstream could produce water level increases of 3-6 meters at locations 40-50 km downstream of dams (ICEM, 2010) when they release water in response to high electricity demand. Unplanned and emergency releases may result in even greater changes.

Run-of-river dams on the Lower Mekong mainstream are not expected to affect flows substantially, but 'hydropeaking' is expected to create substantial short-term hydrological changes. In a few places, re-regulating dams, such as the Sesan 4A dam (Meynell et al., 2014), provide storage that enables the short-term flow variations from hydropeaking to be reduced before the river continues downstream. However, these re-regulating dams are not feasible on very large rivers, including the Mekong mainstream, due to the large storage volumes required to reduce the short-term fluctuations from hydropeaking (ICEM, 2010).

In some cases, more energy can be produced if the power is generated at a location downhill from the dam site. This increases the water pressure, which boosts power production. To divert water, a weir is constructed across the river, immediately downstream of a water intake. By raising the water level of the river, the weir enables the diversion of water to an 'off-site' facility. These off-site facilities can then either discharge the diverted water back into the same river at a downstream location (e.g., the Houay Ho Dam, in southern Lao PDR and the Yali Falls Dam in the central Vietnamese highlands); or into a separate river basin located at a lower elevation (e.g., the Theun-Hinboun and Nam Theun 2 projects in central Lao PDR).

Off-site hydropower generation has different hydrological impacts than dam-site generation. When water is diverted from a river, the overall decrease in flow immediately downstream of a dam can be substantial. Conversely, the turbine outflow can substantially increase flows in the recipient river (e.g., Nam Theun 2 dam diverting water from the Nam Theun River to the Xe Bang Fai River in Lao PDR). Flows in the recipient river can also vary substantially if there is not a re-regulation dam to 'smooth' them out.

Overall, the magnitude of dam impacts on flows tends to decrease farther downstream. Where there are many dams on a single river (a 'cascade') or in a basin, however, the impacts accumulate and are more likely to remain significant far downstream from dams.

Conclusion: *Dams with reservoirs that produce electricity on-site can substantially affect the seasonal timing of the flow. Annual water losses from evaporation are probably small. Run-of-river dams (with little to no reservoir storage) that produce electricity on-site have a minimal effect on the seasonal timing of flow. Dams that divert water for off-site power production dramatically reduce the volume of downstream flows, especially during the dry season. Basins that receive diverted water experience pronounced increases in flow. Hourly and daily fluctuations in electricity demand cause a high degree of flow variability at short timescales. The degree to which on-site dams (the most common type) affect the seasonality of downstream flows depends in part upon the amount of water they keep in their reservoirs relative to the amount of water that they receive. The ways in which dams are operated, however, also affects downstream flows, especially adjustments made to meet fluctuating electricity demands.*

The ecological, economic and social impacts of hydrological change

Between 1960 and 2005, the Mekong River emptied an average of 460 billion cubic meters of water into the South China Sea each year. Typically, 75% of this is discharged between July and October, causing extensive flooding throughout the basin (e.g., Piman et al., 2013a). This tremendous rush of water during the summer monsoon is often referred to as the 'flood pulse'.

Understanding how hydropower development changes these flows is important because many livelihoods based on fisheries and floodplain agriculture have adapted to their natural variations (Stone, 2011; Grumbine and Xu, 2011). While extreme floods threaten human safety, infrastructure, and crops, typical annual floods are beneficial for the fisheries and floodplain agricultural activities. The MRC (2010) has estimated that the average annual economic benefits of floods (US $8-10 billion) are about 138 times greater than their average annual damage costs. In contrast, low-flow hazards, during both the dry and wet seasons, have received less attention than floods, even though droughts register greater economic losses in the basin (MRC, 2010).

The Mekong's fisheries provide a good example of how alterations to hydrology might affect ecology and livelihoods. Sverdrup-Jensen (2002) has suggested that there are seven variables that affect annual fish catches from the Mekong. Four of these are directly related to annual flood characteristics: flood level, duration, timing and regularity. Baran (2006) has argued that changes in dry season discharge will have the greatest impact on fisheries ecology, since the flows may no longer be low enough to trigger fish migration. Long-distance migratory fish species that will be impeded by the development of mainstream dams currently comprise 40% to 70% of the total fish catch in the Mekong basin (Dugan et al., 2010). If all of the proposed dams on the Lower Mekong mainstream are constructed, 55 percent of the river from Chiang Saen (Thailand) to Kratie (Cambodia) will be converted into reservoirs, which could have a profound effect on ecosystems (ICEM, 2010). In addition to the changes in flow that are subject of this review, the obstruction to upstream and downstream fish passage that dams create is considered one of the greatest threats of dam development. Pukinskis and Geheb (2012) provide a more comprehensive review of the potential impacts of dams on the fisheries of the Mekong.

Hydropower dams are also expected to have positive societal impacts, In particular, an increase in dry season flows that could increase the availability of water for off-stream water uses such as irrigation - and in-stream uses - such as navigation (Ringler et al., 2004; ICEM, 2010; Lacombe et al., 2014). In addition, the seasonal regulation of flow extremes enhances hydropower production opportunities downstream of dams, most notably along the Mekong mainstream downstream of the cascade of Chinese dams, also known as the Lancang Cascade.

The impacts of increased dry season flows are not, however, expected to be consistent across the agricultural sector. While increased dry season flows are expected to boost agricultural production for those able to invest in irrigation infrastructure, hydrological changes from upstream hydropower development may force farmers downstream to grow new varieties of rice in response to changes in flood duration (Fox and Wood, 2005). Land traditionally used for riverbank gardens during the dry season may become permanently inundated, including 54% of such gardens on the banks of the Mekong mainstream (ICEM, 2010). Increases in water level could reduce the pumping effort required for some irrigation pumping stations. Almost half of all existing and planned irrigation pump stations on the Mekong mainstream may, however, be negatively impacted by rising water levels upstream of dams that will require pumping stations to be relocated and resized, channel migration downstream of dams, and the need for more complicated controls for dealing with daily flow fluctuations (ICEM, 2010).

In contrast to on-site dams, off-stream production sites often have very small spillway release requirements in the source river (e.g., the Nam Song diversion dam and Nam Theun 2 dam, both in Lao PDR), which may reduce water supply to downstream communities (ADB, 2004) and alter the habitat of fish and other animals that live in the river. Conversely, communities in basins that receive water transferred from other basins for hydropower production (e.g., the Nam Hinboun and Xe Bang Fai basins in Lao PDR) may be especially vulnerable to increased flooding and permanent floodplain inundation (ADB, 2004). While higher water levels during the dry season will improve navigation, case studies from tributaries, including the Nam Song River (Neua, 2007; Miaillier, 2007) and Nam Hinboun River (Southhisombat et al., 2011) suggest that unpredictable water level changes from hydropower diversions may cause losses of fishing gear and threaten human safety.

Conclusion: *Hydropower dams cause ecological, livelihood, economic and social impacts, especially with respect to agricultural and fishing livelihoods. Reduced wet season flows and increased dry season flows will potentially damage the river's ecological productivity and the livelihoods dependent on it. In contrast, increases in dry season flows from hydropower dam reservoirs provide opportunities for irrigation, navigation and hydropower development further downstream. In addition, on-site storage capacity provides flood protection for downstream communities during the wet season. The livelihood and hydrological impacts differ depending on whether or not dams produce power off-stream or on-site. More research on the ecological and livelihood impacts of hydrological alteration is needed.*

What do we know about the hydrological effects of existing Mekong dams?

Studies on the hydrological effects of dams in the Mekong basin can be split into those that focus on observed effects and those that simulate potential impacts using computer models. There are few opportunities to observe the hydrologic effects of dams because most dams in the basin have only recently been constructed, thus not offering sufficiently long flow records from pre- and post-dam periods. The dams under construction and operating along the tributaries of the Lower Mekong River (41 dams) and along the Chinese portion of the mainstream river (6 dams) have a combined storage capacity of 46 billion cubic meters (MRC, 2011), with roughly 23 billion cubic meters in each zone. The Lower Mekong Basin lies within the countries of Thailand, Lao PDR, Cambodia and Viet Nam, while the

Upper Mekong Basin is in China and Myanmar (e.g., MRC, 2005). Since there are no hydropower dams in Myanmar, we henceforth refer to the dams in the Upper Mekong Basin as the Chinese dams.

Chinese Dams

The hydrological effects of the Chinese dams on the Upper Mekong River have been evaluated in both scientific and popular media ever since the Manwan Dam was completed in 1993. Even though this dam, the first of a series of eight dams on the Upper Mekong (ICEM, 2010), has a small storage capacity (260 million cubic meters), its hydrological effects have generated considerable attention (e.g., Stone, 2010; Grumbine and Xu, 2011). Campbell (2007) observes that the media often attributed extremely low flows during the 2003-04 dry season to the Manwan and Dachaoshan dams (commissioned in 2003). Campbell and Manusthiparom (2004) showed that these extreme dry season flows were more severe in Cambodia than in Lao PDR or Thailand, and therefore attribute them to lower than normal rainfall in the Lower Mekong Basin rather than the Chinese dams.

The smaller dams built before Xiaowan have caused only limited hydrological effects since they were commissioned. Campbell (2007) found a statistically significant trend only in decreasing August flows at the Chiang Saen gauging station in northern Thailand, which is close to the Chinese border. Using data from three Chinese gauging stations, Li and He (2008) provide evidence of some dry season flow regulation at the Jiuzhou station downstream of the Manwan and Dachaoshan dams during the dry season and daily and hourly. Lu et al. (2014) also compared pre-dam (1960-1991) and post-dam (1992-2010) flows at Chiang Saen. They observe that daily to monthly flows have become more variable during the dry season, possibly due to irregular water releases from Chinese dams. Like Campbell (2007), they observed a flow decrease in August likely caused by the filling of reservoirs in preparation for the subsequent dry season. They did, however, acknowledge that many other factors might have caused these trends, such as climate change, and stream gauging issues.

However, the hydrologic impacts of the Manwan Dam during its initial filling were more pronounced than those observed afterwards. The extremely low flows observed at Chiang Saen in 1992 have been ascribed to the filling of the Manwan Dam reservoir, even though there was an extreme basin-wide drought that same year (Lu and Siew, 2006; Lu et al., 2014).

To date, no peer-reviewed scientific studies have examined the hydrological effects of the recently commissioned Xiaowan (2010) and Nuozhadu (2014) Dams in spite of their extremely large storage capacity (9.9 billion cubic meters and 12.4 billion cubic meters, respectively - 95% of the 23.2 billion cubic meters of active storage capacity in the cascade) (Lu et al., 2014). Their hydrological effects on the Mekong River during their initial filling periods have not been examined in detail either, although Räsänen et al. (2012) report that the popular press speculated that the filling of the Xiaowan Dam reservoir may have aggravated the low-flow conditions already present during a widespread regional drought in 2010. More studies are needed to verify the accuracy of simulations of the potential impacts of this dam cascade, which are discussed in more detail in the following section.

Lower Mekong Basin dams

There are few opportunities to measure the hydrological impacts of existing hydropower dams due to the absence of pre-dam data on flows, as well as short records following the construction of dams, many of which have been built within the last decade. The Nam Ngum 1 and Theun-Hinboun Dams, however, offer case studies that illustrate the broad range of downstream impacts from on-site and off-stream production schemes, respectively. Using flow records (1962-2009) measured downstream of Nam Ngum 1 Dam, before and after the dam was completed in 1972, Lacombe et al. (2014) showed that current irrigation would compete with environmental flow (i.e. the amount of water needed to maintain the environment) requirements during dry years (i.e., years with less rainfall than normal) if this dam did not exist today. They found that reservoir releases from Nam Ngum 1 have increased dry season discharge by 23% in November, up to 347% in April. In contrast, peak flows in July, during the wet season, amount to 70% of the pre-dam flow due to the dam's large reservoir storage.

The Theun-Hinboun Hydropower Plant is an off-site hydroelectric plant. The facility diverts water from the Nam Theun River to the adjacent Nam Hinboun River, a separate tributary of the Mekong, through a tunnel that takes advantage of the steep elevation gradient between the two rivers to produce energy. The dam is supposed to allow a minimum of five cubic meters per second to continue down the Theun River. The original diversion tunnel to the off-stream power plant conveyed a flow of up to 110 cubic meters per second, and its capacity was doubled in 2012. During the wet season, there is sufficient excess flow to allow water to spill over the Theun-Hinboun dam. In the dry season, however, there is much less water in the Nam Theun River. This means that much of the dry season water is diverted to the Nam Hinboun River. This has negatively impacted the river's fishery. Low flows increase the water temperature and decrease the amount of dissolved oxygen in the water, both of which are harmful to fish (Warren, 1999). To mitigate impacts to the fishery, Warren (1999) recommended that the minimum flow requirement be doubled, which has not yet happened. Upstream of the Theun-Hinboun Dam is the Nam Theun 2 Dam, completed in 2010. This dam diverts water into the Xe Bang Fai River. To compensate for the reduced amount of water reaching the Theun-Hinboun water intake, the Theun-Hinboun Power Company (THPC) has constructed the Nam Gnouang Reservoir on a tributary of the Nam Theun, to regulate water supplied to the Theun-Hinboun Dam (Reis et al., 2014).

The effects of hydropower diversions on the fisheries of downstream reaches have also been documented in northcentral Lao PDR. From 1984 to 1994, the Nam Ngum 1 Dam reservoir failed to reach its full supply level. A canal was therefore built to divert water away from the nearby Nam Song River into the Nam Ngum 1 Reservoir. Miaillier (2007) reports that this diversion reduced the Nam Song River's dry season discharge from ten to two cubic meters per second, severely harming wild capture fish production for more than one thousand families (Neua, 2007).

In contrast to communities downstream of diversions, residents along the Nam Hinboun and Xe Bang Fai rivers must adapt to increased flows as a result of water being transferred into these rivers from the Nam Theun River, especially in the dry season (Souththisombat et al., 2011; Sioudom et al., 2013). A basin-wide evaluation of hydropower diversions has not been conducted.

Very few studies have explored water loss through evaporation from reservoirs. One study (Banafa, 2012) found that the annual evaporation from the Nam Theun 2 Reservoir comprised just 3.6% of its annual inflow.

Finally, the hydrological effects of the construction and initial filling of reservoirs in the Lower Mekong Basin should not be neglected. According to King et al. (2007), the lack of regulation of reservoir filling rates can seriously damage downstream livelihoods and ecosystems. For instance, no water was released downstream from the Nam Lik 1 & 2 project (a single dam) in Lao PDR during its construction in 2010 (Baran et al., 2011). Wyatt and Baird (2007) reported extensive hydrological impacts during the construction of the Yali Falls Dam on the Sesan River in Viet Nam between 1993 and 2001, including an unusually large flood due to the failure of a temporary diversion dam in 1996. Lerner (2003) reported that downstream villagers provided testimony of the deaths of 39 people, who had drowned due to unpredictable water level changes from irregular hydropower releases following the filling of the dam's reservoir in 1998.

Conclusion: *When energy is produced at dam sites with significant storage reservoirs, the main hydrological impacts are increased dry season flows and decreased wet season flows. When water is diverted for off-stream energy production, however, the flow downstream of the dam decreases substantially. In contrast, when water is diverted to other rivers, these must cope with increased average flow. A few case studies in both the Upper Mekong mainstream and Lower Mekong basin tributaries demonstrate that the initial filling of reservoirs following the construction of dams can also reduce downstream flows significantly or create unexpected floods if temporary diversion dams fail during the construction period. No known studies, however, have compared the assumed and observed operating rules for particular dams, because this information is not generally available.*

Only a few English-language studies have evaluated the hydrological effects of the cascade of Chinese dams on the Mekong mainstream (a.k.a. the Lancang cascade) using actual flow records. These studies focus on the smaller dams, and have yet to consider the two largest dams, Xiaowan and Nuozhadu, both of which have been commissioned within the last five years. The effects of the smaller dams on the seasonality of the flow have been shown to be fairly small at the Chiang Saen gauging station on the Mekong River in northern Thailand. Studies have also observed an increase of daily flow variability during the dry season due to irregular releases, and a decrease of daily flow variability during the wet season due to the flow regulation.

Relatively few studies have observed the hydrological effects of dams on Lower Mekong Basin tributaries. As with the dams on the mainstream Mekong in China, Lower Mekong Basin tributary dams with large storage reservoirs (e.g., Nam Ngum 1 Dam in Lao PDR) substantially increase dry season flows and moderately reduce wet season ones. While most dams in the Lower Mekong Basin generate power onsite or at powerhouses immediately downstream, there are some dams used to divert water to power generation sites in other watersheds. In these cases, the flow in rivers from which water is diverted may be depleted substantially, especially during the dry season. But the flow in rivers that receive the diverted water may be augmented dramatically.

What will be the hydrological effects of future dams?

Many studies on the projected impacts of hydropower dams have been conducted. These studies are based largely on work done with hydrological models. Some of these studies assume that other influences on the basin's hydrology, such as climate, water demand and land cover, do not change along with over time. Other studies have explicitly addressed the role that hydropower development could play in mitigating or exacerbating these other hydrological changes. Estimates of future active storage in hydropower reservoirs in the Mekong Basin range from 76 billion cubic meters in 2030 (Hoanh et al., 2010) to between 99 billion cubic meters (Kummu et al., 2010) and 107 billion cubic meters (MRC, 2011) if all proposed dams, including ones without projected commissioning dates, are built. These three potential storage volumes amount to 17%, 21%, and 23% of the Mekong River's mean annual flow (460 billion cubic meters). For comparison, the total storage in the basin in 2008 was just 8.6 billion cubic meters (Kummu et al., 2010), less than 2% of the Mekong's mean annual flow.

Chinese dam studies

The Chinese dams have generated much attention from hydrologists attempting to predict future hydrological changes in the Mekong Basin (e.g., Campbell, 2007; Stone, 2010). A key issue addressed in these studies is how these dams may increase dry season flows, and reduce wet season flows while they fill up their reservoirs. Chapman and He (1996), for example, have estimated that 20% of wet season flows from China will be stored. They also predict that dry season flows at the China-Lao border will increase by 40% following the construction of the Xiaowan Dam, and by 170% following the commissioning of the Nuozhadu Dam.

(No assessments have been conducted to verify these estimates since both of these dams have only been commissioned in the last few years.) Adamson (2001) examined how these two Chinese dams will impact downstream hydrology. He predicted that the difference in flows between wet and dry seasons will be reduced and that the start of the flood season will be delayed by one month. He also found that reallocating 20% of the wet season discharge in the upper Mekong to the dry season would increase average dry season (Dec-May) flows at Chiang Saen by 74%. In addition, he noted that this re-allocation raises the dry season discharge at Kratie (in Cambodia) in March by 50%. At this time of the year, snowmelt from China comprises a much larger proportion of the discharge in the Mekong mainstream. This reallocation between wet and dry seasons would be much milder in the Lower Mekong floodplains during the wet season, however, because so much water is coming in from Lower Mekong tributaries at this time.

As with other studies, the World Bank (2004) predicted that the Chinese dams will increase dry season flows. This increase in dry season flows is important throughout the Lower Mekong mainstream since snowmelt from China produces a disproportionate amount of the total river flow during the dry season. Almost 30 percent of the dry season flow as far downstream as Kratie, Cambodia (just upstream of the delta) originates from China, which contains only 16 percent of the river's drainage area (MRC, 2005). Hoanh et al. (2010) estimated that the dry season discharge will increase by 60% and the wet season discharge will fall by 17%. Räsänen et al. (2012) estimated that the dry season discharge increases by 90% at Chiang Saen, while the wet season discharge decreases by 22%. Their results are similar to those of Adamson et al. (2001) and Hoanh et al. (2010) despite differences in methods between the studies. Räsänen et al. (2012) also predicted a reduction in daily flows during the wet season due to seasonal reservoir re-filling. They also note that more studies are needed on the increased variation in flows due to irregular water releases from dams as well as exceptional dam operations, such as emergency spills.

Some hydropower impact studies have also examined the effects of dams on extreme floods. The World Bank (2004) detected only a small reduction in the water level of the Mekong Delta during extreme floods since the cascade reduces wet season flows much more during dry years than wet ones. Similarly, Piman et al. (2013b) note that hydropower development – in both China and the Lower Mekong Basin - will not reduce the level of flooding throughout the Lower Mekong Basin by more than one percent during a representative wet year (2000). Detecting the future effects of hydropower on flooding in the basin will not be clear-cut due to the complicating effects of other ongoing environmental changes, including climate and land cover.

Tributary hydropower in the Lower Mekong basin

The potential hydrological effects of tributary dams have also been assessed for the Mekong, most notably the Sekong, Sesan and Srepok (3S) Rivers. Some 20% of the Mekong's annual flows come through this tributary basin. Piman et al. (2013a) found that seasonal flow changes produced by existing dams or dams under construction (19 dams in total) are minor in the upper 3S basin, mainly because these dams are small run-of-river dams situated on small tributaries. Yet, 23 additional hydropower projects are proposed, including nine hydropower dams on the main tributaries with substantial reservoir storage. When these projects are also considered, the dry season flows will increase by 63% and the wet season flows will decline by 22%.

Thus, the effects of these tributary dams could be similar to those of Chinese dams. Most importantly, tributary dams are likely to affect the seasonal distribution of flow in the Mekong mainstream much more substantially than the cumulative effects of the twelve run-of-river dams that have been proposed on it (MRC, 2011; Piman et al., 2013b).

The ADB (2004) assessed the Nam Theun 2 project in Lao PDR (12% of the entire Mekong Basin's reservoir storage in 2010), which diverts flow from the Nam Theun River to the Xe Bang Fai River. Discharges from the Nam Theun 2 power plant are expected to double the dry season flows of the Xe Bang Fai, and to increase its wet season flows by 10% (ADB, 2004). The impacts of this transfer will largely be confined to the Xe Bang Fai, as the average annual flow in the Mekong just upstream of its confluence with the Xe Bang Fai is expected to decrease by only 4%. In contrast, Vattenfall Consultants (2008) predicted that the recently constructed Nam Ngum 3 Dam (upstream of Nam Ngum 1) will further reduce seasonal flow extremes downstream of the site where its off-site generation plant discharges water back into the Nam Ngum River 15 kilometers below the dam, although it may also increase flood flows due to emergency releases of water from the dam.

The Tonle Sap Lake ecosystem is very sensitive to changes in the magnitude and timing of seasonal water level changes, following upstream hydropower development (e.g., Lamberts, 2008; Arias et al., 2014a). The maximum and minimum areas of Tonle Sap Lake are expected to decrease and increase during the wet season and the dry season, respectively. Most studies predict that the annual flood will commence one to two weeks later than normal (World Bank, 2004; Baran et al., 2007; Kummu and Sarkkula, 2008), although MRC et al. (2011) predicted that the Tonle Sap flow reversal will begin three days earlier than normal. The discrepancy between these studies has not been addressed.

Baran et al. (2007), Arias et al. (2012), Piman et al. (2013b) and Arias et al. (2014a) all agree that the greatest hydrological impacts to Tonle Sap Lake will be during dry years. While studies generally predict seasonal water level changes of less than one meter, the Tonle Sap Lake ecosystem is very sensitive to small changes in water level (e.g., Lamberts, 2008; Arias et al., 2014b). Overall, 53.5% of the lake's total inflow comes from the Mekong River (mainly via the Tonle Sap River), 34% comes from rivers within the lake's catchment, and the remaining 12.5% comes from direct rainfall onto the lake's surface (Kummu et al., 2013). The effects of tributary dam development on Tonle Sap Lake have also been investigated. Arias et al. (2014b) estimated that 42 new dams in the 3S basin could increase the minimum annual water levels of Tonle Sap Lake by 25-35 centimeters. While these changes in the water level of Tonle Sap Lake may seem modest, they may possibly inhibit tree germination and fish migration in the future (Arias et al., 2014b).

Baran et al. (2007) also found that proposed hydropower and irrigation reservoirs in the Tonle Sap catchment (with a total storage capacity equal to approximately 10% of the total amount of water that flows into the lake) will reduce seasonal lake level extremes. Thus, the potential impact of these Tonle Sap tributary reservoirs alone on the seasonal lake levels is much less than that of hydropower regulation further upstream in the Mekong Basin. However, the additional regulation of flow on these tributaries for hydropower or irrigation purposes could further reduce the seasonal variation in lake levels upon which ecosystems and livelihoods have come to depend.

Mekong Delta

As one moves downstream toward the Mekong Delta, it becomes increasingly difficult to distinguish the effects of upstream water infrastructure development (mainly hydropower and irrigation), climate variability and land-use change on water level variability. This is further compounded by sea level rise (Västilä et al., 2010), and local flood control, irrigation and navigation infrastructure (Le et al., 2007).

Hoa et al. (2008) argue that the maximum water levels of the two main channels in the delta will not be significantly affected by upstream development of water infrastructure. They do find, however, that there will be large increases in water levels in secondary channels, on which embankments and other flood control infrastructure have been recently constructed. While local flood infrastructure benefits some areas and livelihoods, it also increases the duration of flooding and elevates the maximum water level in areas that remain unprotected, which can be harmful to agriculture and compromise human safety (Le et al., 2007; Hoa et al., 2008).

Sea level rise is expected to be the main cause of increased flooding in the delta in the 21st century (MRC, 2010), as the one-meter increase that Carew-Reid (2007) predicted would inundate 30% of the Vietnamese portion of the delta. The effects of sea-level rise diminish as one travels upstream (Västilä et al., 2010) and is expected to be insignificant on the Cambodian floodplain just upstream of the Cambodia/Viet Nam border. No known study has compared the relative effects of sea level rise and embankments on observed or simulated rising water level trends in secondary channels, in spite of the dense population and intense agricultural development of the delta region.

Upstream hydropower development could possibly alleviate the saline intrusion that confines agriculture to a small fraction of the delta by increasing flows during the dry season (e.g., Hoanh et al., 2010; Piman et al., 2013b). In addition, increases in dry season flow could alleviate pollution from acidic groundwater that inhibits dry season agriculture in many areas (Hoa et al., 2008).

Dams and natural disasters

Many models assume that dams will employ relatively simple operating rules that aim to optimize electricity production. Profit maximization, flood control or dam safety objectives are generally not considered in these models. Furthermore, the extent to which reservoir operators adhere to their stated rules is uncertain. Only a few studies (e.g., Lacombe et al., 2014) have compared observed outflows from existing dams with simulated ones to assess the quality of the assumptions on which models are based.

In some cases, it is even possible for dam operators to increase the magnitude of floods if large emergency releases are made in response to concerns about the safety of dams from expected inflows or when operators of different reservoirs do not coordinate their releases in anticipation of floods. The likelihood of dam failure from extreme floods or other natural hazards, such as earthquakes, has not been estimated. Ketelsen et al. (2014) estimated extreme floods at 67 dams in the Lower Mekong Basin and compared them to their reservoir volumes reserved for emergency flood storage and spillway outflow capacity. They found that 40 percent of the 67 dams were not designed to accommodate a flood expected to take place once in every one hundred years on average, although the potential impacts of the failure of these dams vary widely. The maintenance of high reservoir water levels for power generation during the wet season also limits the amount of reservoir storage available for detaining floods. Meanwhile, Pailopee (2014) determined that 14 out of 19 dams on the Mekong mainstream (8 in the Lancang Cascade and 11 on the lower Mekong mainstream) are located within an earthquake source zone.

Conclusion: *Studies predict that dams with reservoirs in the Lancang Cascade and Lower Mekong Basin tributaries will reduce the magnitude of wet season flows and increase the magnitude of dry season flows substantially. Lower Mekong mainstream dams are less likely to alter the distribution of flow between the wet and dry seasons than the dams in China and on Lower Mekong tributaries because they are largely run-of-river dams and only retain a very small proportion of the water that flows to them. They are expected, however, to create substantial changes in flow and water level at an hourly to daily time scale. Lower Mekong tributary hydropower projects include multi-basin diversion schemes, such as the Nam Theun 2 project, which are expected to reduce the flow downstream of dams and increase it in rivers receiving hydropower plant discharges substantially. The cumulative hydrological effects of tributary reservoir storage have begun to be investigated. Reservoir storage in the 3S basin is expected to have an effect on the seasonal distribution of flow in the Lower Mekong floodplains in Cambodia and Viet Nam comparable to that* *of the Chinese dams. Upstream hydropower development is expected to reduce the seasonal water level fluctuations of Tonle Sap Lake upon which many ecosystems and livelihoods depend. In the Mekong Delta, it is difficult to assess the impacts of hydropower development alone because sea level rise and changes in water level from flood control and navigation infrastructure complicate the picture. Future studies must also consider other operator objectives, including profit maximization and flood control, as well as the management of dams during flood events when the failure of dams is of concern.*

Will other ongoing environmental changes mitigate or exacerbate the effects of dams on river hydrology?

Climate

Climate change is another source of future hydrological uncertainty in the Mekong. Several studies have explored this issue using General Circulation Models (GCMs), which are physics-based models of the large-scale circulation of the earth's atmosphere and oceans. They are very important to climate change discussions and efforts to predict what will happen in the future. In the Mekong, the most comprehensive of these studies reveal that (a) climate change will cause significant hydrological changes; (b) researchers in this field do not necessarily agree about what the direction (increase or decrease) and magnitude of these changes will be; and (c) in spite of this uncertainty, the magnitude of climate-induced changes will probably be less than those created by hydropower development, especially during the dry season.

Kingston et al. (2011) use the outputs from seven different GCM models to consider the impact of an average global temperature increase of 2.0 °C on the hydrology at Pakse, Lao PDR along the Mekong mainstream. They found uncertainty in both the direction and magnitude of change in annual low flows (-18.1% to 6.3%), mean flows (-17.8% to 6.5%) and high flows (-16.2% to 8.0%). These wide ranges arise because of uncertainty around future precipitation upstream of Pakse. But all the models predicted that increased surface temperatures will increase potential evapotranspiration rates.

Kingston et al. (2011) predict that the snowmelt season will come earlier, which will increase April-May flow in the upper Mekong basin and reduce the flow in July and August. Cook et al. (2012) showed that three GCMs predict decreases in the March-May snow cover in the upper basin ranging from 20-50%. In contrast, Hoanh et al. (2010) used a different GCM to show that the average snow depth will increase by 62-72%, which will, in turn, increase the snowmelt contribution to flows at the China-Lao PDR border from 5.5-8%. Finally, the contribution of melting of glaciers and permafrost to these changes is expected to be minimal given their small extent in the upper Mekong (Eastham et al., 2008; Hoanh et al., 2010).

Lauri et al. (2012) route the flow predictions from ten climate change scenarios through 126 hydropower dams (116 tributary dams and 10 mainstream dams) to predict the combined hydrological effects of climate change and hydropower development during a period running from 2032 to 2042. At the China – Lao PDR border, wet season flows may decline from 4% to 29% whereas dry season flows are expected to increase between 42% and 70%. (Changes from hydropower reservoirs alone are expected to reduce wet season flows by 17% and increase dry season flows by 65%.) At Kratie, wet season flows may change from -21% to 4% (eight out of ten model runs predict decreases) relative to a 1982-1992 baseline period, while dry season flows are expected to increase between 55% and 79%. (Changes from hydropower alone are predicted to reduce the wet season discharge by 10% and increase the dry season discharge by 68%). These results demonstrate that climate change creates a small amount of uncertainty around the effects of hydropower-induced alteration, especially during the dry season. At both stations, the greatest increases in flow take place toward the end of the dry season, in part due to a shift to an earlier snowmelt season in China. This increase is not, however, substantial enough to eliminate the delayed onset of the flood season that the filling of hydropower reservoirs causes. Finally, one should note that hydropower has the potential to mitigate the increases in wet season flows that some GCMs predict, as they expect the annual five-day maximum flow to change from -15% to 7%.

Lauri et al. (2012) also compared river flow at Kratie between a baseline period prior to the construction of Manwan Dam in China (1982-1992), and a future period (2032-2042), when hydropower development is expected to be largely complete. They found changes in wet season flow ranging from -11% to 15% and from -10% to 13% in the dry season, depending on the GCM used. Flood peaks are expected to increase by between 0 to 20%, while the wet season flow from June to December is expected to change from -17 to 7%. As with Kingston et al. (2011), they also attributed the ambiguous results primarily to the uncertainty about future precipitation changes.

Västilä et al. (2010) explored the combined effects of climate-induced flow changes in the Mekong River and sea level rise on the discharge and water levels of the Lower Mekong floodplains, including the Vietnamese Mekong Delta, the Cambodian floodplains and the Tonle Sap Lake. Using a single GCM to evaluate changes between 2010 and 2049, they found that the average and maximum water levels, along with the flood duration, will increase due to increases in sea level and precipitation. During the dry season, both sea level rise and increases in Mekong River flow from upstream hydropower production will raise the water level. Sea level rise in the near future will mainly affect the water level in the Vietnamese Delta during dry to average years and will not significantly affect the water level of the Cambodian floodplain or the Tonle Sap Lake.

Arias et al. (2012) and Arias et al. (2014a) have estimated the combined hydropower and climate change impacts to the hydrology and ecology of the Tonle Sap Lake using the same ten GCM runs as Lauri et al. (2012). Both studies predict that hydropower will reduce water levels during the wet season and increase them during the dry season. Arias et al. (2014a) show that hydropower development may aggravate the changes in habitat that climate change is expected to cause, most notably expanding the areas of open water (32-38%) and rainfed/irrigation rice (11-21%) while drastically reducing the extent of riverside forests (13-67%) and other seasonally flooded habitats. The ranges of uncertainty reported stems from the uncertainty of GCM model outputs. This wide range of uncertainty shows that long-term basin management decisions must take a wide variety of potential future conditions into account.

There are also a few prominent cumulative impacts studies that have used just a single GCM. Hoanh et al. (2010) simulated the cumulative impacts of hydropower development, climate change and irrigation development. Considering two global greenhouse gas emissions scenarios, they found that dry season discharge may increase by 40-60%, while the wet season discharge will increase between 3-13%. On average, flows on the Mekong will increase by between 2-12%, depending on location. They predicted that increases to average dry season discharge will reduce the area of saline intrusion in the delta by about 14%. Dry season discharge is not, however, consistent from year to year, which may make the extent of saline intrusion of surface waters greater during years with lower than normal dry season flows. Reduced maximum water levels in the Tonle Sap Lake will also reduce its outflow to the delta. Finally, they stress that hydropower reservoirs do not have the storage capacity to mitigate flood increases that may happen under climate change, as they would reduce the seasonally flooded area in the Lower Mekong Basin by less than 1%.

In related analyses, MRC (2011) and Piman et al. (2013b) simulated hydrological changes in the Mekong basin from hydropower, climate and irrigation development. Assuming that there will be 47 hydropower dams distributed throughout the basin, and an additional 3.4 million hectares of land will be irrigated, they predict that average dry season flows at Vientiane will increase by 41%, and average wet season discharge will decrease by 10%. The magnitude of these impacts will decrease downstream from Vientiane because the tributaries that contribute to the flow of the Mekong downstream from Vientiane are expected to collectively regulate a lower percentage of their flow than the Chinese dams are.

These models also predict that the river's flooded area will decline by 6.6% by 2030. However, in 'wet years' (i.e., years with unusually high rainfall), the flooded area will decline by no more than 1%.

Work from the related MRC (2011) and Piman (2013b) studies also suggests that the area affected by saline intrusion in the Mekong Delta will increase by 15% by 2030, but only by an additional 3% further into the future. Increased dry season flows may cause a short-term increase in agricultural production in the delta, but sea level rise is expected to nearly negate this increase by 2030 (MRC, 2011).

Now that the Xiaowan and Nuozhadu Dams have been commissioned, it is expected that hydrological changes from hydropower development will be smaller and will occur at a slower rate (MRC, 2011). A major reason for this is that increases in dry season irrigation are expected to nearly compensate for increases in dry season discharge from new hydropower dams, as the increase in reservoir storage after 2015 is expected to be smaller. These results, as well as those from World Bank (2004) and Hoanh et al. (2010), demonstrate the importance of including future changes in irrigation when projecting long-term impacts of hydropower production. For example, ADB (2004) and Lauri et al. (2012) have predicted that dry season discharges in the Mekong mainstream in 2032-42 will be as much as 70% higher than the ones observed during a 1982-92 baseline period, which precedes the construction of dams on the upper Mekong River. In contrast, the studies that do account for increases in irrigation estimate dry season increases of just 30% to 40% when the effects of hydropower dams are assessed using previously observed discharges.

Water demand

Population growth in the basin will increase the demand for food and, consequently, for irrigated agriculture. Pech and Sunada (2008) estimated that there will be 115-145 million people in the basin by 2050. Barker and Molle (2004) stated that only 2.9% of the basin's land was irrigated in 2002 while Ringler et al. (2004) reported that just 7-10% of the cultivated land in the Lower Mekong basin was irrigated in 1996. Meanwhile, Haddeland et al. (2006) estimated that just 2.3% of average annual flow is used for irrigation, which is low relative to the rest of South and Southeast Asia. Estimating the volume of water withdrawn for irrigation in the Mekong basin is especially challenging, not only due to the lack of data in some places but also because of problems defining which irrigation actually means. For instance, Ringler et al. (2004) distinguished between statistics of equipped irrigated area reported in some previous studies with the gross water-managed area, which includes partial control irrigation, dry- and wet-season supplementary irrigation, as well as flood recession and floating rice production.

Lower Mekong countries plan to increase irrigated area from 6.6 million ha in 2010 to 9.7 million ha in 2030, including an increase in dry season irrigation from 1.2 to 1.8 million ha (MRC, 2011). Hoanh et al. (2010) estimated that the total irrigated area will rise to 8.2 million ha by the same year. MRC (2005) highlights the irrigation potential for Lao PDR and Cambodia, who have far less irrigation infrastructure than northeastern Thailand.

Since Thailand already has the most installed irrigation infrastructure and limited water resources in its northeastern region, an increasing volume of water could be diverted to northeastern Thailand to boost agricultural production (e.g., Molle and Floch, 2008; Sanyu Consultants, 2004). Much of the region's anticipated growth in irrigated agriculture is expected to take place in Lao PDR and Cambodia (ICEM, 2010), some of which is being targeted for international export markets. For instance, the arid Middle Eastern country of Kuwait has looked to purchase large tracts of land in the Tonle Sap basin in Cambodia to meet its own agricultural needs, and is offering to finance dams in return for irrigating this land (Economist, 2009). Foreign investors have also targeted the Vientiane Plain and Mekong River corridor in Lao PDR for agricultural investment (Campbell et al., 2012). More research is needed on the extent to which land allocated for agricultural exports outside of the Mekong may affect irrigation withdrawals from the river and its tributaries.

Groundwater withdrawals for irrigation have increased for Mekong Delta rice cultivation, coffee growing in the highlands of central Viet Nam and southern Lao PDR, and the production of high-value horticultural crops in northern Thailand (Johnston et al., 2010). The effects of these abstractions on surface water sources are not well known.

Domestic and industrial water demand, expected to double by 2030, comprise only a small fraction of total withdrawals (Hoanh et al., 2010; Johnston et al., 2010). Irrigation withdrawals are expected to increasingly compensate dry season increases in discharge from hydropower development (Piman et al., 2013b). The importance of fisheries may, however, restrict irrigation development.

In a hydrologic-economic model of the basin with reservoirs in place in 1990 (when storage was just over one percent of the annual flow), Ringler et al. (2004) detected basin-scale conflicts between in-stream and off-stream demands during the dry season, especially in April, in spite of relatively low allocations of land and water resources for irrigation. This conflict was especially pronounced in northeastern Thailand and the Mekong Delta, the two most intensively irrigated regions in the basin. In a comparison of their 1990 baseline scenario with three alternative hydropower development ones, they found that increased dry season flows from hydropower development alleviate conflicts between in-stream and off-stream water use during the dry season. While hydropower diminished this dry-season allocation conflict, they noted that the expected losses from fisheries and wetlands exceed expected gains from irrigation. An updated version of this hydrologic-economic model that takes recent hydropower development into account has yet to be made.

One other major issue with hydropower dam development is the need to resettle people that new dams and reservoirs displace. For instance, ICEM (2010) estimates that dam construction on the Lower Mekong mainstream alone would force over one hundred thousand people to be resettled. The effects of water consumption changes that result from resettlement programs, especially irrigation projects, on basin water availability have not been investigated in detail.

Land cover

While land cover inputs are used in many hydrological models of the Mekong Basin (e.g., Kite, 2001; Kiem et al., 2008; Costa-Cabral et al., 2008) and smaller catchments (e.g., Ty, 2011; Ly, 2011), few studies have taken advantage of them to simulate hydrology under different future land cover scenarios, especially at the Mekong basin scale. No studies have coupled spatially explicit land cover change scenarios with hydropower development scenarios at basin scale either. In tributary basins, only Ty (2011) have done this on the Srepok (3S Basin). They discovered that changes in land cover and water demand outweigh the effects of hydropower development along most river reaches, although the most severe hydrological alteration takes place immediately downstream of dams due to hydropower production. Difficulties in acquiring reliable long-term datasets of land cover, including forested areas, of the basin make it hard to determine the hydrologic effects of forest cover change at the basin scale (Costa-Cabral et al., 2008).

Indirect changes in land cover from dam development projects must also be considered. For instance, Orr et al. (2012) estimated that land for livestock production would need to increase by 63% (assuming no intensification of livestock production) in order to compensate for the 40% loss in protein from a reduced fish catch, but do not evaluate the spatial patterns of such a change. This prevents an analysis of the hydrological effects of such changes in land cover at particular locations within the Mekong basin.

In addition, no studies have predicted how hydrological alteration may permanently compromise the role that existing floodplain wetlands play in reducing flood peaks and providing storage that can naturally supply streams with water during periods with little or no rain.

Conclusion: *Climate change is expected to be the other major driver of hydrologic change during the 21st century, although its impact is not nearly as pronounced as the impact of a 126-dam development. Studies that apply multiple General Circulation Models (GCMs) to the Mekong basin demonstrate that there is uncertainty about whether flows will increase or decrease during both the wet and dry seasons, and the extent to which these changes may affect ecosystems and livelihoods. Uncertainty in the direction (an increase or decrease) of snowmelt changes due to varying projections of snowfall in the Upper Mekong inhibits estimates of future dry season discharge. One consistent result among climate change studies is that an earlier snowmelt period is expected to increase discharge from the Upper Mekong in the late spring, at the beginning of the wet season. The flow-reduction impacts from the refilling of hydropower reservoirs during the early part of the wet season are, however, expected to be greater.*

Population growth is increasing food demand. Increased dry season flows will provide an opportunity to meet this growing demand through expanded irrigation allowed by land availability. However, the livelihoods of many agricul-

tural stakeholders may be compromised due to the loss of riverbank gardens and the need to relocate, redesign, and change the operation of irrigation pumping stations. In the near future, increases in dry season irrigation withdrawals are small relative to the impacts on flow delivered by the Xiaowan and Nuozhadu dams in China. By 2030, however, irrigation withdrawals are expected to nearly compensate for changes from hydropower-induced flow regulation in the Mekong mainstream during the dry season. Changes in water demand due to the resettlement of people following the construction of dams have not been widely investigated.

Changes in land cover affect hydrological processes. Few studies, however, have examined the hydrological implications of land cover change in the Mekong basin as a whole. Changes in land cover that dam development projects induce are only beginning to be researched and their hydrological effects have only been studied in specific tributary basins. Spatially explicit models of future land cover change are needed to assess its potential hydrological impacts.

What do we need to know to better manage the hydrological impacts of hydropower development?

The existing gauging network often does not cover small watersheds in which dams are being constructed, which often prevents simulated hydrological impacts from being compared with observed ones, and makes it much more difficult to adapt models to small watersheds. The lack of precipitation stations in Lao PDR and Cambodia also limits the accuracy of many basin-wide models.

Data on the sub-daily flows downstream of dams in the lower Mekong would enable studies on the livelihood impacts of these changes. Additionally, the public availability of daily flow time series and reservoir operating rules from China would allow the upper Mekong impacts from hydropower development to be better assessed.

Many recent studies have indicated that the magnitude, and even the direction, of the effects of climate change on the hydrology of the basin are uncertain. Thus, the extent to which hydropower reservoirs will mitigate or exacerbate these changes is difficult to judge. Unknown future demographic and economic changes on water demand and land cover provide additional uncertainty. Studies that assess the effects of the uncertainty of GCMs of future climate, and hydrological models on the basin hydrology are emerging (e.g., Lauri et al., 2012; Thompson et al., 2013; Arias et al., 2014a).

Conclusion: *The continuation of hydrological monitoring efforts in the basin is essential for creating the post-dam hydrological records that are necessary for assessing the hydrological impacts of hydropower dams. Methods of estimating and extending pre-dam records at dam sites for which relatively few data are available are also needed. These studies of observed hydrological impacts are important because many simulation models make assumptions that limit their accuracy. More studies on ecological and livelihood responses to hydrological alteration are also needed as are studies that integrate the impacts of hydropower development with changes in climate, water use and land cover. Differences in the research agendas of national, supranational and non-governmental organizations can inhibit such integrative research efforts.*

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The CGIAR Research Program on Water, Land and Ecosystems in the Greater Mekong (WLE Greater Mekong) is a research-for-development initiative that seeks to improve the governance and management of water resources by generating and sharing the knowledge and practices needed to do so. Balancing the costs and benefits of water, food, energy and the environment is essential for sustainable growth, and the program works to address this challenge in the Irrawaddy, Mekong, Red and Salween river basins. WLE Greater Mekong works through a wide range of partners and builds on the work of the CGIAR Challenge Program on Water and Food (2002-2014). The program is based in Vientiane, Lao PDR.

WLE is a global research program that promotes a new approach to sustainable agricultural intensification in which a healthy functioning ecosystem is seen as a prerequisite to agricultural development, resilience of food systems and human well-being. This program is led by the International Water Management Institute (IWMI), a member of the CGIAR Consortium, and is supported by CGIAR, a global research partnership for a food secure future.

In the Greater Mekong, the WLE works to generate and share the knowledge and practice needed to improve the governance and management of water resources in the Greater Mekong. If it is successful, water will be governed more fairly, water governance will be better-informed, accounting for downstream users. Capacity to govern and manage water will be improved and ecological functions and health will be accounted for.

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