LET ALL RIVERS RUN TO THE SEA

Climate Change Mitigation through Reservoir Removal & Watershed Management

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The notion that hydropower is "clean," or otherwise carbon-neutral, is misguided. A review of the latest scientific literature makes it clear that hydropower is not nearly as climate-friendly as has previously been assumed. Several factors combine to make extreme caution necessary before expanding hydroelectric generation, and suggest that alternative avenues of renewable energy would be preferable. This paper proposes decommissioning "traditional" hydropower in favor of run-of-the-river generation schemes, preventing new reservoir construction, and adopting sustainable land reclamation practices in the former inundation zones. It also urges the incorporation of an ecological calculus for dam removal into the REDD+ framework. Taken in sum, this measures urged in this paper should account for at least 25 gigatonnes of CO_2 equivalent removed from the atmosphere by 2060, along with improved health of river ecosystems worldwide.

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INTRODUCTION

There can no longer be any reasonable doubt that the planet is undergoing a dramatic climactic shift. At the heart of climate change (or, more properly, climate disruption) is the greenhouse effect, "in which molecules of various gases trap heat in Earth's atmosphere and keep it warm enough to support life."[1] It is true that "[c]arbon dioxide (CO_2) and other 'greenhouse gases' (GHGs) are an important part of Earth's natural cycles."[2] However, since the Industrial Revolution, human burning of fossil fuels has raised atmospheric GHG concentrations to dangerous levels.

We underestimate the effect of climate change on the water supply at our own peril. "A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events."[3] According to NOAA, 2012 was the warmest year on record for the continental United States.[4] Observed average global temperatures have risen by 1.5ºF since 1900.[5] Current projections place temperatures increasing by another 2 to 11.5ºF by 2100,[6] though these estimates are often being revised upward. The world's glaciers are already retreating, and without their moderating influence on the water supply, the major river basins of the world are likely to become even less predictable or reliable.

As global surface temperature has risen, the oceans are also gradually warming. As the world's oceans warm, the El Niño-Southern Oscillation (ENSO) has become more variable, and therefore more intense.[7] As a result, the "catastrophic floods, droughts, disease outbreaks, wildfires and even social unrest" linked to the weather cycle are likely to see similar increases in intensity.[8] Likewise, "[w]armer ocean waters cause sea ice to melt, trigger bleaching of corals,

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[1] Alice McKeown and Gary Gardner, *Climate Change Reference Guide and Glossary*, WORLD WATCH INST., http://www.worldwatch.org/files/pdf/CCRG.pdf

[2] *Id*.

[3] Intergovernmental Panel on Climate Change (IPCC), *Summary for Policymakers*, *in* MANAGING THE RISKS OF EXTREME EVENTS AND DISASTERS TO ADVANCE CLIMATE CHANGE ADAPTATION (SREX), 7 (2012).

[4] Lauren Morello & ClimateWire, *2012 Proves Warmest Year Ever in U.S.*, SCIENTIFIC AMERICAN (Jan. 9, 2013), http://www.scientificamerican.com/article.cfm?id=2012-proves-warmest-year-ever-in-us.

[5] GLOBAL CLIMATE CHANGE IMPACTS IN THE UNITED STATES, 9 (Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson eds., 2009), www.globalchange.gov/usimpacts.

[6] *Id*.

[7] Lauren Morello and ClimateWire, *Study Strengthens Link between El Niño and Climate Change*, SCIENTIFIC AMERICAN (Jan. 4, 2013), http://www.scientificamerican.com/article.cfm?id=study-strengthens-link-between-el-nino-and-climate-change.

[8] *Id*.

result in many species shifting their geographic ranges, stress many other species that cannot move elsewhere, contribute to sea-level rise, and hold less oxygen and carbon dioxide."[9] As sea ice melts, it reduces (and in fact reverses) the albedo effect – ice reflects virtually all sunlight, whereas sea water absorbs heat much more readily. In addition, the seas are one of the major natural carbon sinks, but "recent studies suggest that their ability to absorb CO_2 may be declining significantly."[10] The end result is that as the warming trend progresses, it is likely to pick up momentum.

The combination of extreme storm events and ocean chemistry changes likely to accompany global climate disruption portends increased infiltration of saltwater into our aquifers.[11] Increased erosion and sedimentation is also likely as the land changes for the worse. A world of unchecked climate change is one where lands of former abundance die slow deaths at the hands of desertification. It is a reality in which our supply of fresh water is imperiled by regular flood, water pollution and drought. Increased withdrawals of groundwater can and will cause subsidence in the land, and dry ground will be increasingly subject to erosion by wind as well as rain. Whole river basins will face the risk of a slow death by dehydration, if they are not killed by expanding brackish zones first. Even though we only know some the possible consequences of failure, they are sufficiently dire to necessitate action.

In the face of these potential consequences, many nations are looking to develop their hydropower potential. They hope to ensure fresh water and consistently available power for their populations, using a perceived "clean" technology. Unfortunately, hydropower is not nearly as climate-friendly as previously assumed. While the goal of divesting national energy portfolios of fossil fuels is laudable, encouraging unrestricted hydropower development is ultimately counterproductive. The deforestation and GHG emissions which result from reservoir formation – particularly in tropical zones – mean that extreme caution is required before expanding hydroelectric generation.

Make no mistake; we will have to take proactive measures to combat climate change. While global policymakers dither over the future of our energy supply, and those with financial interest in continued use of fossil fuels fight to preserve the status quo, life on Spaceship Earth

[9] National Research Council, ECOLOGICAL IMPACTS OF CLIMATE CHANGE, 4, (National Academies of Science, 2008), http://www.nap.edu/catalog/12491.html.
[10] Wold, *et al*. (eds.), CLIMATE CHANGE AND THE LAW, Ch.1 § II.B, at 9 (Matthew Bender & Co, Inc. 2009).
[11] *See, e.g.*, Post, V.E.A., *Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead?*, 13 HYDROGEOL. J. 120 (2005).

faces increasingly (and alarmingly) severe challenges. In order to prevent a frankly hellish future, or at least mitigate it, we need to cut net global carbon emissions "by about 8 billion tons per year by 2060, keeping a total of ~200 billion [metric] tons [gigatonnes] of carbon from entering the atmosphere."[12] As a means of dividing the overarching goal into more manageable action items, Socolow and Pacala recommend the adoption of at least eight carbon-reduction "wedges."[13] Each wedge "represents an activity that reduces emissions to the atmosphere that starts at zero today and increases linearly until it accounts for 1GtC/year of reduced carbon."[14] Each wedge thus accounts for a reduction of approximately 25 gigatonnes of CO_2 equivalent (CO_2eq) emissions by 2060.

This paper proposes a suite of mitigation measures in order to achieve at least one wedge, unified by an underlying focus on responsible water management and protection. Part I reviews the current literature on greenhouse gas emissions from artificial reservoirs. Part II proposes decommissioning traditional hydropower in favor of run-of-the-river generation schemes, preventing new reservoir construction and adopting sustainable land reclamation practices in the former inundation zones. These include reforestation efforts and establishment of riparian buffers; it briefly discusses use of sustainable agricultural practices. Though it touches on "small hydropower" alternatives to the lost generation capacity from dam removal, global electricity demand is largely outside the scope of this paper. Taken in sum, the measures urged herein could provide several wedges worth of net carbon reductions.

I. HYDROPOWER AND GREENHOUSE GAS EMISSIONS

One of the oldest forms of "renewable" energy comes from hydropower. Historically, people have built dams "to provide water for irrigated agriculture, domestic or industrial use, to generate hydropower or help control floods."[15] From ancient grain mills to tanneries to hydroelectric generation, humanity has long harnessed the power of flowing water. At present, approximately one-fifth of the world's electricity comes from hydropower, with China, Canada, Brazil, the United States and Russia leading the generation pack. A typical hydro plant is a system with three parts: an electric plant for electricity production; a dam that can be opened or

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[12] Carbon Mitigation Initiative, Princeton University, http://cmi.princeton.edu/wedges/intro.php. *See also*, R. Socolow and S. Pacala, *A Plan to Keep Carbon in Check*, SCIENTIFIC AMERICAN, Sept. 2006, at 50

[13] Carbon Mitigation Initiative, *supra* note 12.

[14] Stephen Pacala & Robert Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, 305 SCIENCE 968 (Aug. 13, 2004).

[15] The World Commission on Dams, *Dams and Development: A New Framework for Decision-Making – The Report of the World Commission on Dams*, 1 (Nov. 2000) [hereinafter WCD Report].

closed for water flow control; and a reservoir for water storage.[16] There are two main types of hydroelectric generation: storage and run-of-river. The former requires a dam, whereas the latter places a turbine in the natural flow of the stream.

Per kilowatt-hour, hydroelectric generation is one of the easiest, cheapest and most reliable sources of electrical power (renewable or otherwise) presently available. However, we have long known that significant environmental harms accompany hydropower.[17] More recently, research into the warming effects of traditional reservoir hydropower have cast doubt on its status as a "carbon friendly" generation technology. Since run-of-river schemes create small or no reservoirs, these contributions to climate disruption are primarily limited to "traditional" hydropower. Though there is some debate over the full scope of GHG impact,[18] there is a general consensus that artificial reservoirs are significant contributors to total GHG emissions. To be specific, one of the key contributing factors to the uncertainty surrounding GHG emission from hydroelectric generation within rivers is biomass decomposition. "[T]he rate of decomposition is also highly dependent not only on the climate zone (e.g., tropical, boreal, etc.), but also on the specifics of the flooded biome (e.g., old river, wetlands, forest, etc.)."[19] Unfortunately, this means that increasing temperatures will result in exponentially increasing GHG emissions from reservoirs.

A. Reservoir Emissions: Sources, Studies, & Projections

Once a dam is erected, it fundamentally alters the hydrological characteristics of the site. The subsequent flooding inundates former forests and riparian zones, creating lake-like conditions. Flowing water settles, depositing silt and other organic matter on the new littoral bottom. The water stratifies into varying temperature levels, with accompanying variation in dissolved oxygen levels. The decomposition of the submerged organic matter generates carbon dioxide and methane.[20] Methane production is particularly prevalent in warmer, shallower waters. Similarly, in nitrogen-enriched, aerated reservoirs, various microbial processes also lead

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[16] NATIONAL GEOGRAPHIC, *Hydropower: Going with the Flow*, http://environment.nationalgeographic.com/environment/global-warming/hydropower-profile/.
[17] *See, e.g.*, *National Wildlife Federation v. Gorsuch*, 693 F.2d 156 (D.C. Cir. 1982)
[18] *See, e.g.*, Joel Avruch Goldenfum, *Challenges and solutions for assessing the impact of freshwater reservoirs on natural GHG emissions*, 12 ECOHYDROLOGY & HYDROBIOLOGY 115 (2012).
[19] William Steinhurst, Patrick Knight, and Melissa Schultz. *Hydropower Greenhouse Gas Emissions: State of the Research*, at 2 (Feb. 14, 2012), http://www.clf.org/wp-content/uploads/2012/02/Hydropower-GHG-Emissions-Feb.-14-2012.pdf [hereinafter *Hydropower GHG Emissions*].
[20] Cary Institute of Ecosystem Studies, *Greenhouse gas impact of hydroelectric reservoirs downgraded*, SCIENCEDAILY.COM (August 1, 2011), http://www.sciencedaily.com- /releases/2011/08/110801134733.htm.

to the production of nitrous oxide. Since the vast majority of the undeveloped hydropower potential is in tropical or subtropical countries,[21] and such reservoirs result in the highest rates of production of GHG emissions, construction of new impoundment-style hydro plants should face increasing opposition from the global community.

The initial flooding phase "is associated with particularly high rates of both bacterial activity and GHG production."[22] Alarmingly, greenhouse gas emissions from hydropower may be higher than annual emissions for some fossil fuel sources during this period.[23] In addition, following the massive pulse of GHG emissions "in the first few years post-inundation, emissions can continue at a lower but still substantial rate."[24] Reservoirs emit all three biogenic GHGs (carbon dioxide, methane, and nitrous oxide):

> "In reservoirs, CO_2 [carbon dioxide] can be produced under oxic or anoxic conditions, in the water column and in the sediments. CH_4 [methane] is produced under anaerobic conditions, mainly in the sediments, and released preferentially in shallow waters. N_2O [nitrous oxide] can be produced mainly in the drawdown zone of a reservoir, as an intermediate by-product of two microbiological processes (nitrification and denitrification), mainly at the sediment/water interface."[25]

Research into emissions from reservoirs indicates that the biophysical characteristics of a pre-inundation basin area are determinative as to the degree of GHG emissions likely to occur, post-flooding.[26] While older reservoirs and run-of-river schemes have relatively low GHG emissions (0.5-152 kg CO_2eq/MWh),[27] newly flooded boreal reservoirs, over their lifetime, may have emission rates from about 1/3 to nearly 2/3 that of a natural gas combined-cycle plant (160 ~ 250 kg CO_2eq/MWh),[28] with first-year emissions approaching 700 kg CO_2eq/MWh.[29] In terms of hydropower, "[c]arbon emissions are correlated to reservoir age and latitude, with the highest emission rates from the tropical Amazon region."[30] Tropical reservoirs have high water

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[21] *See, e.g.*, Kumar, A., *et al.*, *Hydropower, in* IPCC SPECIAL REPORT ON RENEWABLE ENERGY SOURCES AND CLIMATE CHANGE MITIGATION [O. Edenhofer, *et al.*(eds)], 445, Figure 5.2, Cambridge University Press (2011).
[22] Nathan Barros *et al.*, *Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude*, 4 NATURE GEOSCI. 593, 593 (2011).
[23] *Hydropower GHG Emissions*, at 9.
[24] Yang, H., & Flower, R. J., *Potentially massive greenhouse-gas sources in proposed tropical dams, in* 10 FRONTIERS IN ECOLOGY & ENVT. 234, 234-235 (2012).
[25] Goldenfum, *supra* note 18, at 116.
[26] *Id.*
[27] *Hydropower GHG Emissions*, Table 1, at 2
[28] *Id.*
[29] *Id.*, Table 4, at 9.
[30] Barros *et al.* 2011, *supra* note 22, at 593.

temperatures and rapid decomposition, producing anoxic conditions and a high proportion of methane.[31] The net result is that, over a 100-year lifetime, a tropical storage hydropower project will likely have GHG emissions of 1,300-3,000 kg CO_2eq/MWh.[32] By comparison; a new coal-fired plant is estimated to produce 900-1,200 kg CO_2eq/MWh over the same 100-year lifecycle.[33]

As another example, a series of dams is currently planned on the Mekong River in Southeast Asia, which would inundate a combined 2,120 square kilometers.[34] Although there is a general lack of data as regarding Southeast Asian reservoirs specifically, "the latest global estimation has indicated that tropical (25˚N–25˚S) hydroelectric reservoirs can emit 844.7 milligrams CO_2–C per square meter per day (mg CO_2–C m^{-2} d^{-1}) and 2.2 mg CH_4–C m^{-2} d^{-1}."[35] According to Yang & Flower, if the dams are constructed as planned, they could cumulatively contribute 2.5 Mt CO_2eq/year.[36] However, "[b]ecause this recent emissions estimate is a global average that includes many older reservoirs … the actual impacts of the planned dams on the Mekong River are likely to be much higher, especially in the first few years."[37]

The practice of river impoundment has already flooded vast areas. Hydroelectric reservoir creation has inundated approximately 340,000 square kilometers worldwide.[38] These reservoirs comprise approximately 20% of all reservoir area.[39] In other words, an area the size of the Greenland ice sheet[40] is underwater and emitting greenhouse gases, especially in warmer months.[41] The results of a study of the drawdown marshes in the Three Gorges Reservoir Region (TGRR)[42] are more worrying. There, Chinese scientists estimated that the methane emission of littoral marshes, which covered only 10% of the surface area of the Three Gorges Reservoir

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[31] D.M. Rosenberg *et al.*, *Large-scale impacts of hydroelectric development*, 5 ENVTL. REV. 27 (1997), http://www.environmental-expert.com/Files%5C6455%5Carticles%5C7571%5C18sep18-A97-001.pdf
[32] *Hydropower GHG Emissions*, Table 1, at 2.
[33] *Id.*
[34] Yang & Flower, *supra* note 24, at 234.
[35] *Id.*
[36] *Id*.
[37] *Id.* (*internal citations omitted*). *See also* Fearnside, P.M., *Methane emissions from hydroelectric dams*, SCIENCE (E-Letter 28 July 2011), http://www.sciencemag.org/content/331/6013/50.short/reply#sci_el_14254, *accord*. Fearnside, P.M. & S. Pueyo, *Underestimating greenhouse-gas emissions from tropical dams*, 2 NATURE CLIMATE CHANGE 382 (2012).
[38] Barros *et al.* 2011, *supra* note 22, at 593.
[39] *Id*.
[40] That is, 1.7 million square kilometers (1.7M km^2 x (20%) = 340,000 km^2).
[41] *See, e.g.*, Del Sontro *et al*., *Extreme Methane Emissions from a Swiss Hydropower Reservoir: Contribution from Bubbling Sediments*, 44 SCI. & TECH. 2419 (2010).
[42] Chen, *et al.*, *Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir*, 114 J. GEOPHYSICAL RES. D18301 (2009).

(TGR) "was about 19% of the total [methane] emission from the surface of TGR."[43] A recent study in Washington State similarly found that "methane emissions jumped 20-fold when the water level [in a reservoir] was drawn down."[44] As drawdowns are necessary to the large-scale hydroelectric generation process, this data presents cause for concern.

Yet another emerging area of concern comes from aquatic nitrogen flux and emissions of nitrous oxide from aquatic environments. At a basic level, the global overloading of waterways with nitrogen –most often via fertilizers – means that emissions of nitrous oxide from global waters have increased in response.[45] This is because "aquatic ecosystems are potential hot-spots for N loss given that denitrification is favored in sediments and hypoxic or anoxic bottom waters, particularly in systems with abundant organic carbon (C) and nitrates."[46] Due in part to the increase in nitrogen loading from nonpoint agricultural runoff, it is likely that "aquatic [nitrous oxide] production is roughly equivalent to all terrestrially-based [nitrous oxide] sources in the US."[47] For reference, the IPCC has indicated that nitrous oxide has a global warming potential of 310 times that of CO_2, on a 100-year timescale.[48]

It is true that reservoir emissions of nitrous oxide "have been poorly investigated, but the potential is high since many reservoirs are eutrophic with high N loads from surrounding watersheds."[49] What little data we currently have indicates that "in boreal reservoirs, the contribution of [nitrous oxide] to gross GHG emissions is usually less than 1%, while, in some tropical reservoirs, the contribution … can vary from nearly 0 to 30%."[50] Normally, "in eutrophic marine or freshwater systems, anoxic deep waters mostly act as a sink for [nitrous oxide] produced either by nitrification or denitrification at the transient zone between oxic and

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[43] *Id*., § 4.2
[44] Washington State University, *New global warming culprit: Methane emissions jump dramatically during dam drawdowns*, SCIENCEDAILY.COM (August 8, 2012), http://www.sciencedaily.com-/releases/2012/08/120808081420.htm.
[45] Anu Liikanen, *et al.*, *Spatial and seasonal variation in greenhouse gas and nutrient dynamics and their interactions in the sediments of a boreal eutrophic lake*, 65 BIOGEOCHEMISTRY 83, 84 (2003).
[46] John A. Harrison, *et al*., *The regional and global significance of nitrogen removal in lakes and reservoirs*, 93 BIOGEOCHEMISTRY 143, 144 (March 2009).
[47] J. S. Baron, *et al.*, *The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States*, BIOGEOCHEMISTRY, at *11 (October 23, 2012), http://link.springer.com/article/10.1007/s10533-012-9788-y.
[48] Solomon, S., *et al.* (eds.), *Climate Change 2007 - The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 141, Table 2.1, http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4_wg1_full_report.pdf.
[49] Baron, *et al.* 2012, *supra* note 47, at *13.
[50] Goldenfum, *supra* note 18, at 116.

anoxic water layers."[51] However, "[h]igh [nitrous oxide] emissions have been measured from eutrophic, nitrogen loaded freshwater."[52] For example, a recent Chinese study "found that deep waters of reservoirs used for hydroelectric generation were supersaturated with [nitrous oxide] year-round, as was water directly downstream."[53] This suggests that deep waters released for hydropower are additional sources of nitrous oxide production from reservoirs. It may be that "the longer residence times of waters retained by dams enhance denitrification, primary production, and the burial of organic N in sediments."[54] In addition, many reservoirs are artificially oxygenated in some form or fashion, due to water quality concerns.[55] Since artificial oxygenation eliminates "anoxic conditions in the hypolimnion that formerly favored [nitrous oxide] reduction… artificial oxygenation might increase net production of [nitrous oxide] and therefore increase [nitrous oxide] emissions to the atmosphere."[56]

The combined worldwide emissions of GHGs from all reservoirs are projected to reach 0.90 $GtCO_2eq$/year in 2050.[57] However, "[c]onsidering the estimate of the reservoirs' area ranging from 0.26 M km^2 to 1.5 M km^2, and the technically exploitable hydropower capacity of [14653×10^9 kWh/year]," the total GHG emissions from artificial reservoirs could reach 2.7 to 5.4 billion tonnes of CO_2 equivalent per year.[58] Assuming a rise of reservoir-based GHG emissions to "only" 2.7 Gt/year by 2050, targeted dam removal (particularly in the tropics), easily has the potential to account for at least a single mitigation wedge. If rising temperatures cause a larger net increase in reservoir-based emissions, achieving a mitigation wedge through dam decommissioning would be even simpler. As shown, shallow reservoirs in particular tend to favor increased production of both methane and nitrous oxide. Given the excessively productive nature of shallow-basin and tropical reservoirs, prevention and removal of dams in these areas should receive priority.

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[51] Liikanen, *et al.* 2003, *supra* note 45, at 84.
[52] *Id.*
[53] Baron, *et al.* 2012, *supra* note 47, at *13 (*citing* Liu X-L, Liu C-Q, Li S-L, Wang F-S, Wang B-L, Wang Z-L, *Spatiotemporal variations of nitrous oxide (N_2O) emissions from two reservoirs in SW China*, 45 ATMOS. ENVT. 5458 (2011)).
[54] *Ibid*.
[55] *Gorsuch*, 693 F.2d at 47-50.
[56] Martin Mengis, René Gächter, & Bernhard Wehrli, *Nitrous oxide emissions to the atmosphere from an artificially oxygenated lake*, 41 LIMNOL. OCEANOGR. 548, 552 (1996).
[57] Li, S.Y. & Lu, X.X., *Greenhouse gas emissions from reservoirs could double within 40 years*, SCIENCE (28 June 2011), www.sciencemag.org/content/331/6013/50/reply. For reference, 1Pg = 1000 Tg = 1000 Mt = 1Gt.
[58] *Id*.

B. Post-Reservoir Problems

Despite the tangible environmental benefits to be achieved, removal of dams comes with its own set of problems. The world's population is growing, and putting increasing demands on global water resources. Similarly, increasing populations demand greater food production, which tends to promote industrial agriculture. Implementing industrial agriculture, without appropriate safeguards, results in long-term soil degradation, releases stored carbon, and increases nutrient loads to waterways.[59] As noted, reservoirs compound and exacerbate many of these effects. Rather than rely on traditional reservoirs, deployment of in-channel withdrawal systems that do not involve damming[60] or strategic creation of off-stream reservoirs[61] can supply fresh water for municipal and agricultural needs. These withdrawal systems can do so without the potential negative environmental effects discussed above which result from traditional reservoirs, etc. Moreover, increased efficiency in water use – through improved infrastructure and water conservation measures – can provide substantial amounts of water without extracting greater quantities from rivers and streams.[62]

Beyond the constraints imposed by global population growth and need for water storage, more and more countries are industrializing. With increased industrialization comes a concomitant increase in demand for electricity. Since hydropower is generally cheaper and more reliable per unit power than other non-fossil technologies, it is likely that increased industrialization will correlate with increased power generation/consumption. Given that most developing nations are located in tropical or subtropical regions, and possess the majority of undeveloped hydropower potential,[63] substituting run-of-the-river hydroelectric generation systems for traditional impoundment systems would help offset the loss of generation capacity. There will also be a need to compensate for removing the flood-control benefits of dams. Likewise, concerns regarding "water conservation, potability, and access to water"[64] mean that a

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[59] *See generally* Stöckle, *et al.*, *Carbon storage and nitrous oxide emissions of cropping systems in eastern Washington: A simulation study*, 67 J. SOIL & WATER CONSERVATION 365 (2012).
[60] *See* James G. March, *et al.*, *Damming Tropical Island Streams: Problems, Solutions, and Alternatives*, 53 BIOSCIENCE 1069 (Nov. 2003).
[61] *Id.*, at 1074-75.
[62] *Id.*, at 1075.
[63] *See supra*, note 21.
[64] Hirokawa, Keith H. and Rosenbloom, Jonathan D., *Land Use Planning in a Climate Change Context* (October 30, 2012), *in* RESEARCH HANDBOOK ON CLIMATE ADAPTATION LAW (Jonathan Verschuuren, ed., 2013, Forthcoming); Drake University Law School Research Paper No. 12-33; Albany Law School Research Paper No. 21 for 2012-2013. Available at SSRN: http://ssrn.com/abstract=2168925.

goal of total reservoir decommissioning is unrealistic, at present. If dams cannot be removed, operating jurisdictions should take "three steps for bringing multi-objective reservoir operation closer to the goal of ecological sustainability: (1) conduct research to identify which features of flow variation are essential for river health and to quantify these relationships, (2) develop valuation methods to assess the total value of river health and (3) develop optimal control softwares that combine water balance modelling with models that predict ecosystem responses to flow [*sic*]."[65]

C. Run-of-River/Small Hydropower

As mentioned, small-scale hydroelectric systems would be a necessary component in a post-reservoir infrastructure plan. Deployment of such systems would help obviate the need for existing dams; many countries may be unwilling to forego the power supply of a hydroelectric facility without a ready replacement. Run-of-the-river hydropower, alternately called "small hydropower" or "small hydro,"[66] is "distinct from traditional hydropower in that it is defined by generation capacities of 30 MW or less, per site."[67] To produce power, these facilities "divert some of a river's flow through a pipe or tunnel leading to electricity generating turbines and subsequently return the water downstream."[68] Consequently, they do not require dams or reservoirs, thereby mitigating many of the environmental impacts associated with hydropower.[69]

In addition, small-scale hydropower can be "one of the most cost-effective energy technologies to be considered for rural electrification in less developed countries."[70] Especially when compared to large-scale hydropower, run-of-the-river has rapid deployment time, minimal administrative costs, and is far less maintenance-intensive. Over the past decade, "small hydro projects producing power outputs in the range 1-10kW [have been] gaining popularity, particularly as isolated power supply schemes for village electrification."[71] "However, relatively

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[65] H.I. Jager and B.T. Smith, *Sustainable Reservoir Operation: Can We Generate Hydropower and Preserve Ecosystem Values?*, 24 RIVER RES. APPLICATIONS 340, 340 (2008).
[66] *See* Oliver Paish, *Small hydro power: technology and current status*, 6 RENEWABLE & SUSTAINABLE ENERGY REV. 537, 538 (2002) ("In the jargon of the industry, 'mini' hydro typically refers to schemes below 2 MW, micro-hydro below 500 kW and pico-hydro below 10 kW.")
[67] Lea Kosnik, *The potential for small scale hydropower development in the US*, 38 ENERGY POL'Y 5512, 5512 (June 2010).
[68] Mark Jaccard, Noel Meltonn, and John Nyboer, *Institutions and processes for scaling up renewables: Run-of-river hydropower in British Columbia*, 39 ENERGY POL'Y 4042, 4045 (Mar. 2011).
[69] *Id. See also* NAT'L RENEWABLE ENERGY LAB., SMALL HYDROPOWER SYSTEMS 2 (2001), available at http://www.nrel.gov/docs/fy01osti/29065.pdf
[70] Paish 2002, *supra* note 61, at 537.
[71] J. B. Ekanayake, *Induction generators for small hydro schemes*, POWER ENGINEERING J. (April 2002), at 61.

higher installation costs (in $/kW) are a barrier to the development of many low-head and/or low-power sites,"[72] at least in the United States.[73] On the other hand, "after upfront capital costs have been recouped, long-term operating costs [of hydropower] are amongst the lowest of all generating technologies."[74] Under the Clean Development Mechanism (CDM)[75] of the Kyoto Protocol, it is possible for countries to receive international funding in order to deploy small hydro.[76] Thus, small-scale hydropower generation should figure prominently in any developing nation's energy portfolio; supplanting large-scale hydropower would be ideal.

II. RECLAIMING INUNDATION ZONES

As reservoir infrastructure ages, the impounding dams become increasingly ripe for outright removal or redevelopment as small hydro plants. In developing a removal calculus for dams, the international community should include size, geophysical characteristics, latitude and age in determining which impoundment structures to target.[77] Regardless of the actual proportion of reservoirs removed, there will be a major land-use reform which comes with the decommissioning of dams. The underlying philosophy of former reservoir area reclamation should be that "[a]ll successful restoration measures have to be based on sound ecological principles and an understanding of hydrologic processes."[78] Particularly in the tropics, the fragmentation of ecosystems which has accompanied reservoir construction has generally decreased their efficacy in respiring and sequestering carbon.[79]

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[72] Qin Fen (Katherine) Zhang *et al.*, SMALL HYDROPOWER COST REFERENCE MODEL, 2, *prepared by* Oak Ridge National Laboratory, ORNL/TM-2012/501 (Oct. 2012).

[73] Zhang, *et al.*, *supra* note 72, estimate that the initial capital cost "could range from $2000/kW to $7500/kW for small scale hydro and from $2500/kW to $10,000/kW for mini-hydro, which would result in [a levelized cost of energy] of $45–120/MWh (typically, $83/MWh) for small hydro and $55–185/MWh (typically, $90/MWh) for mini-hydro, assuming annual [operation and maintenance] cost is 1.5–2.5% of initial investment." *Id.*, at 14.

[74] Manfred Lenzen, *Current State of Development of Electricity-Generating Technologies: A Literature Review*, 3 ENERGIES 462, 470 (2010).

[75] Established pursuant to Article 12 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), Dec. 10, 1997, U.N. Doc FCCC/CP/1997/7/Add.1, 37 I.L.M. 22 (1998) [hereinafter Kyoto Protocol].

[76] *See, e.g.*, A.K. Akella *et al.*, *Social, economical and environmental impacts of renewable energy systems*, 34 RENEWABLE ENERGY 390, 391 (2009); Christoph Sutter & Juan Carlos Parreño, *Does the current Clean Development Mechanism (CDM) deliver its sustainable development claim? An analysis of officially registered CDM projects*, 84 CLIMATIC CHANGE 75 (2007).

[77] *See generally* N. Leroy Poff & David D. Hart, *How Dams Vary and Why It Matters for the Emerging Science of Dam Removal*, 52 BIOSCIENCE 659 (Aug. 2002).

[78] Kai Jensen, *et al.*, *Restoration ecology of river valleys*, 7 BASIC & APPLIED ECOLOGY 383, 385 (2006).

[79] *See generally*, Eben Broadbent, *et al.*, *Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon*, 141 BIOLOGICAL CONSERVATION 1747 (2008). *See also* Fearnside, P.M. and Laurance, W.F., *Tropical deforestation and greenhouse gas emissions*, 14 ECOLOGICAL APPLICATIONS 982 (2004);

Following dam decommissioning, "[d]ewatering and elimination of the reservoir results in dramatic changes soon after … as extensive areas of featureless sediment and previously submerged structures come into view."[80] The former littoral bottom generally lacks any form of soil fixation, and is therefore extremely vulnerable to erosion. Similarly, "invasions of exotic plants are sometimes associated with increased nitrogen availability, and soils containing high micronutrient or heavy metal levels may support only plants tolerant of these ions."[81]

A sustainable combination of reclamation measures following dam decommissioning is necessary to reverse ecological damage. These measures should include responsible reforestation, well-designed and managed riparian buffers, and carbon-friendly agricultural practices. As an added incentive, these practices could help to complete any partial mitigation wedges left by the dam removal process. Moreover, successful reforestation and reestablishment of riparian buffers would serve as effective flood control substitutes.[82]

A. Reforestation

As mentioned, basin-wide deforestation is one of the major ecological changes induced by river impoundment. Already, from our experience with CDM projects and Amazon basin reclamation efforts, we know that caution is necessary in any reforestation project. Indeed, just like hydroelectric development, "forestry projects carry significant environmental and social risks."[83] Despite the mandates of the Convention on Biological Diversity[84] to "[r]ehabilitate and restore degraded ecosystems"[85] and "[p]revent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species,"[86] many reforestation projects have fallen decidedly short.

Reforestation projects developed under the CDM "usually consist of a monoculture plantation of fast-growing, non-endemic tree species that sequester large amounts of carbon, but have significantly lower biodiversity values than native vegetative landscapes and can threaten

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W.F. Laurance, *et al.*, *Ecosystem Decay of Amazonian Forest Fragments: a 22-Year Investigation*, 16 CONSERVATION BIOLOGY 605 (2002).

80 E.H. Stanley and M.W. Doyle, *Trading off: the ecological effects of dam removal*, 1 FRONTIERS IN ECOLOGY & ENVT. 15 (Feb. 2003).

81 Patrick B. Shafroth, *et al*., *Potential Responses of Riparian Vegetation to Dam Removal*, 52 BIOSCIENCE 703, 704 (Aug. 2002).

82 WCD Report, "Integrated Flood Management," at 160 *et seq.*

83 Kylie Wilson, *Access to Justice for Victims of the International Carbon Offset Industry*, 38 ECOLOGY L.Q. 967, 1012 (2011)

84 Convention on Biological Diversity (CBD), June 5, 1992, 1760 U.N.T.S. 79.

85 CBD *supra* note 57, art. 8(f).

86 *Id*., art. 8(h).

endemic ecosystems."[87] In light of the problems brought on by CDM reforestation projects, the international community has since developed a new methodology focusing on reducing emissions from deforestation and forest degradation in developing countries.[88] Otherwise known as REDD+,[89] the framework "provides financial incentives for forest nations to halt deforestation and restore forests though sustainable forestry practices."[90] "At least in theory, REDD+ lends itself to bridge the divide between developed and developing country Parties, providing a testing field for large-scale climate change mitigation in the latter, with projected expeditious results."[91]

As a way to provide additional financial incentive under REDD+, there has been some suggestion of reforestation with high-value commodity crops. Unfortunately, "[s]cientific knowledge of methods for regenerating high [economic] value species in natural forests is weak almost everywhere."[92] In places "[w]here systems for tropical silviculture have been worked out, it is most often for regenerating monocultures of [economically] valuable species, or managing mixtures with costly and intensive treatments."[93] In addition, it bears mentioning with any such project that "if living trees are harvested the fate of the carbon depends on the end use of the forest products."[94] That is, "carbon may be stored for many years in durable wood products such as construction timber, but for only a few years in paper and pulp, before being released back into the atmosphere as CO_2."[95] That said; "[f]acilitating natural tree regeneration may be an important management option, but significant barriers to tree regeneration must be overcome."[96]

In developing any reservoir reforestation effort – under REDD+ or not – countries would do well to remember a central maxim of conservation biology: "[t]he less data or more

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[87] Wilson, *supra* note 58, 38 Ecology L.Q. at 1012.
[88] *See* UNFCCC, Reducing emissions from deforestation in developing countries. Approaches to stimulate action: Submission from Parties, UN Doc. FCCC/CP/2005/MISC.1, 6 December 2005.
[89] *See* Decision 1/CP.16: Outcome of the Ad Hoc Working Group on Long-term Cooperative Action Under the Convention, paras. 68-79, UN Doc. FCCC/CP/2010/7/Add.1, 15 March 2011 [hereinafter Cancun Agreement].
[90] Jay Tufano, *Forests and Climate Change Policy: An Analysis of Three Redd-Plus Design Options*, 4 CARBON & CLIMATE L. REV. 443, 443 (2011)
[91] Annalisa Savaresi, *Chapter 15 the Role of Redd in the Harmonisation of Overlapping International Obligations*, 21 IUS GENTIUM 391, 394 (2013)
[92] Lloyd C. Irland, *"The Big Trees Were Kings": Challenges for Global Response to Climate Change and Tropical Forest Loss*, 28 UCLA J. ENVTL. L. & POL'Y 387, 399 (2010)
[93] *Id.*, at 399-400.
[94] Oscar J. Cacho, Robyn L. Hean and Russell M. Wise, "Carbon-accounting methods and reforestation incentives," 47 AUSTL. J. AGRIC. & RESOURCE ECON. 153, 155 (June 2003).
[95] *Id.*
[96] Elaine Hooper, *et al.*, *Responses of 20 Native Tree Species to Reforestation Strategies for Abandoned Farmland in Panama*, 12 ECOLOGICAL APPLICATIONS 1626, 1626 (Dec. 2002). *See also supra* notes 61-62 and accompanying text.

uncertainty involved, the more conservative a conservation plan must be."[97] "All else being equal, large populations are less vulnerable than small populations to extinction [and] large blocks of habitat are … less likely to experience a disturbance throughout their area."[98] This guiding principle of continuity, along with the previously-mentioned edge effects of forest fragmentation, makes corridor unification a good starting goal for any post-reservoir reforestation effort. However, "restoration plantings are probably an option that can only be used in a relatively small number of situations and rarely in the most severely degraded tropical landscapes, except where the potential environmental benefits or costs of inaction (as in mined land or mangrove restoration) may justify the required investment."[99]

Presuming that REDD+ can allow such efforts to be successful, the restoration of ecological flow in formerly disrupted habitat could pay additional "ecological services" dividends. For instance, "native trees have been shown to improve soil conditions significantly within four years on badly degraded tropical land."[100] Once fully reestablished, the new forest would also serve as an effective riparian buffer. Ultimately, the process of dam removal should lead to restoration of pre-inundation habitat, in order to maximize reduction of GHG emissions.

C. Riparian Buffers

Simply having the legal and economic framework in place to encourage reforestation, however, is insufficient. As noted,[101] there is generally a spike in GHG emissions which accompanies water drawdowns. Moreover, the "riparian vegetation that grows in post–dam removal environments interacts strongly with other factors that are generally given more direct consideration in dam removal efforts."[102] Invasive species often colonize the alluvial silt left over from dam removal.[103] Therefore, former inundation zones will require constant monitoring and maintenance while in the process of reforesting. As an example, the Elwha River is currently undergoing a three-year restoration process, to be completed in the summer of 2014. When the process is complete, the National Park Service will have removed both the Glines Canyon and

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[97] Reed F. Noss, *Some Principles of Conservation Biology, As They Apply to Environmental Law*, 69 CHI.-KENT L. REV. 893, 898 (1994)
[98] *Id.*, at 901.
[99] David Lamb, Peter D. Erskine, and John A. Parotta, *Restoration of Degraded Tropical Forest Landscapes*, 310 SCIENCE 1628, 1629 (Dec. 2005).
[100] Elaine Hooper, *et al.*, *supra* note 96, at 1626.
[101] *E.g.*, *supra* notes 23-24, 41-45 and accompanying text.
[102] Shafroth, *et al.* 2002, *supra* note 81.
[103] Shafroth, *et al.* 2002, *supra* note 81; Stanley & Doyle 2003, *supra* note 80.

Elwha Dams, and will begin restoring the pre-dam ecosystem. The progress so far indicates that "a slow removal, using natural hydrologic erosion to rebuild the river channel [is] the best option for restoration."[104] However, "scientists estimate that it will take about thirty years for the Elwha River to return to its normal flows and sediment loads."[105] When establishing remediation plans, then, it is crucial to account for the necessary time-frame.

In order to prevent excessive organic matter and fertilizer-enriched agricultural runoff from reaching freshwater reservoir systems, we must also implement some form of control for diffuse surface flow.[106] As noted, the addition of organic matter to a reservoir can stimulate CH_4 production. By implementing a natural filter of vegetation around the global riverine system, we can reduce the amount of methane production via depriving the biological processes of source fuel. If such a filter buffer consists of native primary-succession vegetation, a further reduction in net carbon could occur. Similarly, riparian buffers could help reduce the nitrate loads of aquatic ecosystems.[107] As demonstrated, the excessive nitrogen concentration in both the water column and in lentic sediments is a contributing factor to GHG production in reservoir systems.

There is a large body of work indicating that the sterile commercial varieties of vetiver[108] are "efficient in sand stabilization, soil and water conservation, erosion control, reclamation of degraded lands, soil reclamation, ecological rehabilitation and remediation of soils contaminated with heavy metals."[109] In particular, vetiver "has been proven to reduce the concentration of the metals such as Al, Mn, As, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Zn."[110] This, combined with its deep roots,[111] would appear to make vetiver an ideal candidate for use in post-reservoir remediation procedures. Due to the fact that hedgerow vetiver does not germinate and must be propagated by

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[104] Michael C. Blumm & Andrew B. Erickson, *Dam Removal in the Pacific Northwest: Lessons for the Nation*, 42 ENVTL. L. 1043, 1058 (2012).
[105] *Id*.
[106] *See generally*, V. Polyakov, A. Fares, and M.H. Ryder, *Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: A review*, 13 ENVTL. REV. 129 (2005).
[107] *See*, *e.g.*, Timothy B. Spruill, *Statistical Evaluation of Effects of Riparian Buffers on Nitrate and Ground Water Quality*, 29 J. ENVTL. QUALITY 1523 (Sept. 2000).
[108] *Chrysopogon zizanoides* L. Roberty, also known as *Vetiveria zizanoides* L. Nash. A tropical grass, thought native to India & Southeast Asia; commonly used in perfumery, often used for soil control in its native lands, now grown worldwide in tropical and subtropical zones.
[109] Majda Khalil Suleiman, *et al.*, Vetiveria zizanoides *Plantation for Slope Stabilization in Kuwait: A case study*, 2 J. AG. & BIODIVERSITY RES. 44, 45 (Feb. 2013). *See also* Kayode Steven Are, *et al.*, *Comparative Effects of Vetiver Grass (*Chrysopogon zizanioides*) Strips, Vetiver Mulch and Veticompost on Soil Quality and Erodibility of a Sloping Land*, 45 AGRICULTURA TROPICA ET SUBTROPICA 189 (Dec. 2012).
[110] Sarwoko Mangkoedihardjo and Yuli Triastuti, "Vetiver in Phytoremediation of Mercury Polluted Soil with the Addition of Compost," 7 J. APPLIED SCI. RES. 465, 465 (Apr. 2011).
[111] Often reaching 5m in length. *See supra* notes 109-110.

cuttings, "it is a very well-behaved grass throughout the tropics and subtropics."[112] Consequently, it has seen increasing use for soil enrichment and erosion control over the past 25 years in a variety of tropical and subtropical countries.[113] As vetiver is already a cash crop– notably in Brazil and Indonesia – additional financial incentives could accompany its use for riparian buffer creation and initial reservoir restoration.

D. Responsible Agriculture

Beyond riparian buffers, we should encourage further reduction of agricultural runoff through the implementation of sustainable agricultural practices. "Throughout the tropics, economically marginal subsistence farmers are being displaced from prime agricultural lands and forced to colonise steep lands."[114] Thus, if a jurisdiction which decommissions a dam declines to restore the pre-inundation ecology, the basin should at least receive consideration as a potential cultivation site. Considering the relative richness of the reservoir silt, it could be an attractive alternative to additional deforestation. In addition, sustainable soil management and control techniques – cover crops, reducing periods of bare fallow, etc. – and alternative planting methods – no till, ridge-till, chisel plow planting, etc. – would reduce the amount of organic material which washes into reservoirs through erosion.[115]

These practices would help mitigate GHG emissions on several levels. First, although "inputs to and removal rates from aquatic systems are influenced by climate and management, reduction of N inputs from their source will be the most effective means to prevent or to minimize environmental and economic impacts"[116] of excess reactive nitrogen in the world's water resources. By reducing nutrient-enriched stormwater runoff through better agriculture, farmers can help reduce benthic production of nitrous oxide.[117] Second, mitigating erosion translates into less organic carbon for microbial processes to convert into methane. Likewise, these practices also help to reduce the aeration of soils, thereby retaining more stored carbon.

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[112] R.P. Adams, *et al.*, *DNA fingerprinting reveals clonal nature of* Vetiveria zizanioides *(L.) Nash, Gramineae and sources of potential new germplasm*, 7 MOLECULAR ECOLOGY 813, 814 (1998).
[113] *Id.*, at 813.
[114] Hellin, J. and Haigh, M.J, *Impact of* Vetiveria zizanioides *(Vetiver Grass) Live Barriers on Maize Production in Honduras*, *in* 3 PROCEEDINGS OF THE 12TH INTERNATIONAL SOIL CONSERVATION ORGANIZATION [ISCO] CONFERENCE Beijing, China, May 26-31, 2002, at 277 (Jiao Juren, *et al.*, eds.), http://tucson.ars.ag.gov/isco/isco12/VolumeIII/ImpactofVetiveriaZizanioides.pdf.
[115] *See* Socolaw & Pacala, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, 305 SCIENCE 968, 971 (2004).
[116] Baron, *et al.* 2012, *supra* note 47, at *2.
[117] *See supra* Part I.A.

CONCLUSION

As shown, hydropower is not nearly as climate-friendly as previously assumed. Carbon dioxide, methane and nitrous oxide are persistent biological byproducts of the concentrations of organic matter and agricultural runoff present in artificial reservoirs. These emissions increase with temperature, reservoir aeration, and water level drawdowns. In determining priority removal projects, the international community should develop an ecological calculus. The ecological removal calculus should also apply to the determination of Certified Emission Reductions. At a minimum, prevention of tropical reservoir creation and decommissioning dams which already exist would provide a significant reduction in anticipated GHG emissions.

Beyond dam removal, the addition of responsible land-use and inundation-zone reclamation practices would further reduce hydropower- and reservoir-linked GHG emissions. As demonstrated, there are existing technologies which could provide the power generation, water resource and flood control benefits of any decommissioned dams. The REDD+ framework, once finalized, should provide tropical nations which choose to reduce their hydrological impacts incentive and aid to do so. In particular, REDD+ should encourage reforestation of former reservoir areas. In the alternative, the alluvial silt of the reservoir bottom would provide effectively "free" agricultural land, mitigating the need for deforestation. Taken in sum, these measures would easily account for a mitigation wedge, if not more than one.

In the event that these alternatives are insufficient to discourage reservoir creation, even when properly incentivized by the international community, countries should be mindful of several things. First, the creation of any dam must be factored into the relevant carbon budget. Second, countries must adhere to their responsibilities under international instruments such as the Convention on Biological Diversity. Likewise, the methodology proposed in the World Commission on Dams 2000 Report must control: countries must include "all stakeholders in the decision-making process and specifically [address] cultural resource protection and [accord] it the same weight as all other factors."[118] Finally, whatever course of action they choose to pursue, countries must incorporate solid ecological science and all available environmental mitigation measures to maintain "natural" ecological flows in their planning. Otherwise, they will end up exacerbating the damage caused by the creation of a new large-scale reservoir, and make an already bad situation worse.

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[118] Michael P. Lawrence, *Damming Rivers, Damning Cultures*, 30 AM. INDIAN L. REV. 247, 255 (2006)