CLIMATE SCIENCE

Renewable but not carbon-free

Hydroelectric energy is renewable, but reservoirs contribute to climate change by releasing carbon dioxide and methane to the atmosphere. A global estimate suggests that young reservoirs in low latitudes produce the largest emissions.

Bernhard Wehrli

Hydropower is the most important source of renewable energy available. Worldwide, hydroelectric reservoirs contribute about 16% of total electricity production[1]. The industrialized nations have already used the best sites for hydropower production. However, in the developing world, more projects are lining up that are often controversial. More than 45,000 large dams have been built[2], and reservoirs cover a total area as large as the Caspian Sea. Yet the alteration of large river systems can have serious environmental consequences, and human-made reservoirs affect the climate through the emission of greenhouse gases. Writing in *Nature Geoscience*, Barros and colleagues[3] present a meta-analysis and global extrapolation of emissions of carbon dioxide and methane from hydropower reservoirs, and — despite remaining large uncertainties — conclude that the emissions are lower than thought.

When hydroelectric dams are built, local and regional consequences can be severe. Societal concerns include the collapse of migratory fish populations, displacement of local people and coastal erosion downstream, because sediment particles are trapped in the reservoir and thus unavailable to stabilize coastline dynamics. Nonetheless, hydropower is often considered an environmentally friendly energy production, particularly if local environmental impacts can be mitigated[4]. Yet the issue of greenhouse gas emissions from reservoirs is often omitted: for example, a protocol for assessing hydropower sustainability published by the International Association of Hydropower last month[5] postpones this controversial topic, because a methodology approved by the industry is still lacking.

The assessment of emissions of the potent greenhouse gas methane (CH_4) is particularly complicated: methane is emitted through three distinct pathways, only two of which can be quantified accurately (Fig. 1). Methane is produced in the absence of oxygen at the bottom of lakes and in the sediments. In the first pathway, the dissolved gas diffuses towards the oxygen-rich surface layers. There, it is partially oxidized in the presence of microorganisms, and partially released into the atmosphere at the lake surface, depending on surface concentration and wind speed. Because the surface concentration is usually relatively uniform, these emissions can be quantified quite accurately. In a second pathway, methane is released from water as it passes the turbines downstream of the reservoir. The turbine discharge is usually well documented and the methane concentration near the intakes can be easily quantified. So this second flux, too, is fairly well constrained. And emissions through this pathway can be reduced by optimization of the turbine intake. The third potential release rate, however, is difficult to measure. When methane production is high, methane gas bubbles can form and rise to the surface at a fast rate. This process, termed ebullition, is extremely heterogeneous in space and time. As a result, estimates using the conventional flux chamber method have large measurement errors.

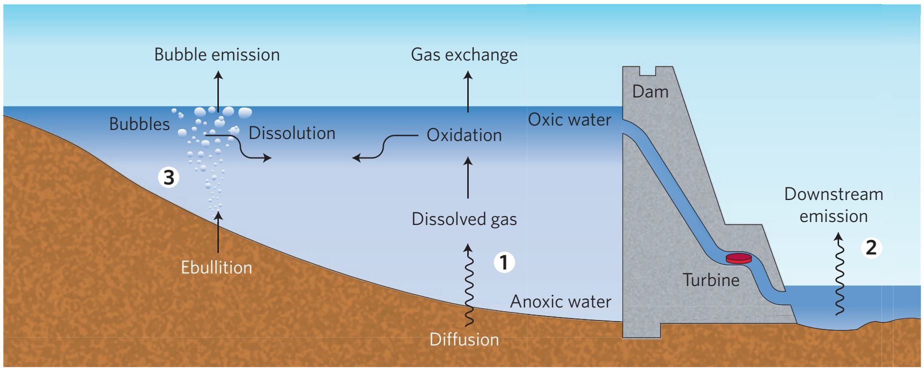

Figure 1 | Schematic methane emission pathways from a hydroelectric reservoir. In sediments with slower methane formation and at greater depths, dissolved methane diffuses upwards (1). The methane enters the atmosphere through gas exchange at the surface. Emissions may be reduced by microbial oxidation at the interface between the oxic and anoxic water layers. Second, downstream emissions after the water has passed the turbine (2) depend on the stratification of the reservoir and the vertical position of the main water intake. Finally, in sediments with high methane production rate, bubbles form when the methane solubility is exceeded (3). Some of this methane dissolves from the rising bubbles but a large fraction is rapidly emitted to the atmosphere. Barros and colleagues[3] estimate emissions of carbon dioxide and methane from 85 hydroelectric reservoirs worldwide, but because the third pathway is poorly constrained by measurements, uncertainties remain large.

Barros and colleagues[3] present flux calculations from hydroelectric reservoirs for both methane and carbon dioxide. Their estimates are based on a compilation of published emission studies from 85 reservoirs, ranging from boreal latitudes to the tropics. All reservoirs were found to be sources of methane, and 88% showed a net emission of CO_2. But emission rates spanned four orders of magnitude. Statistical analysis revealed that reservoir age and latitude are important factors that influence emission rates. The greenhouse gas fluxes from older reservoirs, however, often remain high beyond the time expected for submerged soils and vegetation to release their carbon. These initial contributions from the establishment of a reservoir were clearly not the sole drivers for greenhouse gas production.

The global greenhouse gas emission rates derived by Barros and colleagues, of 48×10^{12} g C as CO_2 and 3×10^{12} g C as CH_4, represent only about 4% of the estimated global carbon emissions from inland waters. These estimates are lower than those based on a more limited number of sampled reservoirs[6]. Nevertheless, because of the remaining large uncertainties in the estimates, it would be premature to conclude that greenhouse gas emissions of hydropower operations could be dismissed as insignificant.

In particular, only about half of the flux measurements cited by Barros and colleagues included an assessment of methane release by bubble emission. Together with the large overall variability between reservoirs, this poorly constrained pathway adds a significant range of uncertainty to the global estimate. Methane emissions through bubble flux therefore deserve special attention in future studies. Expanding the database will be facilitated by emerging techniques such as hydro-acoustic measurements[7], eddy-covariance estimates or systems-analysis approaches[8] that allow a more integrative coverage of emission fluxes. Assessing methane emissions through ebullition represents a particularly important priority in large reservoirs, where the variety in the vegetation and soil types that were submerged when the dam was built adds to the spatial variability in emission fluxes[9].

Barros and colleagues[3] indicate that greenhouse gas fluxes from artificial lakes might be slightly lower than estimated previously. But to tighten the uncertainty ranges, and to help the industry reduce methane and carbon dioxide emissions by building optimized, greener hydropower reservoirs, we will need to improve our understanding of the key drivers of emissions. ❒

Bernhard Wehrli is at Eawag, the Swiss Federal Institute of Aquatic Science and Technology, Seestrasse 79, CH-6047 Kastanienbaum, Switzerland.
e-mail: wehrli@eawag.ch

References

1. International Energy Agency *Electricity/Heat in World in 2008*; available via http://go.nature.com/6mAAWK
2. World Commission on Dams *Dams and Development: A New Framework for Decision-Making* (Earthscan, 2000). Available via http://go.nature.com/rnFEBI
3. Barros N. *et al. Nature Geosci.* **4,** 593–596 (2011).
4. Bratrich C. *et al. River Res. Applic.* **20,** 865–882 (2004).
5. http://hydrosustainability.org/
6. St. Louis V. L. *et al. Bioscience* **50,** 766–775 (2000).
7. Ostrovsky I. *et al. Limnol. Oceanogr. Meth.* **6,** 105–118 (2008).
8. DelSontro T. *et al. Environ. Sci. Technol.* **44,** 2419–2425 (2010).
9. Teodoru C. R. *et al. Ecosystems* **14,** 28–46 (2011).

PLANETARY SCIENCE

Water on the Moon

Analysis of the first Apollo samples suggested that Earth's only satellite was bone dry. Spacecraft data and improved analysis techniques now indicate that the Moon is more volatile-rich and complex than previously thought.

David J. Lawrence

Our understanding of water and other volatile components on the Moon has changed dramatically over the past 10 to 15 years. Following innovative spaceflight missions to the Moon, as well as new laboratory analytical capabilities for studying lunar samples, the term 'water on the Moon' is no longer an oxymoron. At the Lunar and Planetary Institute conference[1] on *A Wet vs. Dry Moon* held in Houston in June 2011, planetary scientists concluded that water and volatiles are key ingredients to both the Moon's history and its present environment.

Numerous studies that demonstrated the Apollo lunar samples contained hardly any volatiles led, in part, to the idea that the Moon formed during a giant impact with the Earth[2]. The impact would have generated intense heat that could have caused the volatiles, including those in the deep lunar interior, to evaporate and be lost to space. However, even if the Moon had lost its own water long ago, over time it could still have collected water and hydrogen from elsewhere in the Solar System. For example, icy comets could deliver water to the Moon, and atoms of hydrogen could be deposited on the lunar surface by the incoming solar wind. It was therefore thought that volatile materials could be accumulating at the Moon's permanently shaded polar regions, where they can, in principle, be stored for geological periods of time without significant loss[3,4].

The prediction of enhanced hydrogen concentrations at the poles proved correct. In 1998, the orbiting Lunar Prospector spacecraft measured the abundance of elements on the Moon's surface using neutron spectroscopy. These orbital neutron measurements provided firm evidence for enhanced hydrogen concentrations, and by inference water, at both of the Moon's poles[5]. Radar reflection data from NASA's Lunar Reconnaissance Orbiter and the Indian Space Research Organisation's Chandrayaan-1 spacecraft, have since shown that around 600 million cubic metres of water are contained in permanently shaded craters at the lunar north pole[6] (Fig. 1). NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) identified many volatile species in a plume of material expelled when the empty Centaur stage of the Atlas V launch vehicle was intentionally crashed into Cabeus crater in October 2009, indicating the existence of volatiles near the Moon's south pole[7]. More surprisingly, orbital measurements of reflectance have identified ubiquitous surface water and hydroxyl, another volatile hydrogen/oxygen compound, in non-polar regions[8–10].

In parallel with analyses of the new orbital data, a re-evaluation of volatile species in the Apollo samples is being carried out. Improvements in analytical techniques have made it possible to perform highly sensitive isotopic measurements on very small lunar grains. These analyses are revealing water in Apollo samples that were once thought to be dry[11–15]. Furthermore, many of the samples may have preserved information from the Moon's deep interior, implying that the lunar mantle may contain significantly more water than previously thought.

The influx of new data has generated many questions relating to the Moon's formation, evolution and present-day environment. For example, it is unknown how much water is stored on the Moon, particularly at the poles, what factors control

Correction

In the News & Views 'Renewable but not carbon-free' (*Nature Geosci.* http://dx.doi.org/10.1038/ngeo1226; 2011), the first sentence of the final paragraph should have read 'Barros and colleagues[3] indicate that greenhouse gas fluxes from artificial lakes might be slightly lower than estimated previously'. This error was corrected in all versions of the text on 17 August 2011.