In comparison, the potential cost of doing nothing could reach €3.7 trillion across the entire country[5], and even the cost of a single dyke failure could range from €10 to 50 billion. It is unlikely that the entire low-lying coastal area would be flooded, but a dyke break in a densely populated area would cause massive property loss and damage. The recommendations have an added financial flexibility: the infrastructure modifications and growth can be made in a stepwise fashion, and are designed so that they can be readily upgraded if scenarios for future sea-level rise change.

An unexpected opportunity

Unsurprisingly, these relatively costly suggestions have become a source of occasionally heated public, political and academic debate. Yet even with existing uncertainties about future climate, economically viable and responsible investments into adaptation measures in the water safety sector and beyond can be made in the Netherlands. These measures call for innovative solutions and technologies in our struggle against the rising waters. We thus propose that rather than being a financial burden, coastal protection can be seen as a push to boost technological innovation, and to invest in the development of long-lasting and sustainable infrastructure. We, and the Delta Committee, suggest that for the Netherlands, climate change can be an opportunity for societal and economic growth and evolution, moving the country into a sustainable future. ❐

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References

1. Kabat, P., Van Vierssen, W., Veraart, J., Vellinga, P. & Aerts, J. *Nature* **438,** 283–284 (2005).
2. http://www.deltacommissie.com/
3. Church, J. A. & White, N. J. *Geophys. Res. Lett.* **33,** L01602 (2006).
4. http://www.deltacommissie.com/doc/deltareport_full.pdf
5. Aerts, J., Sprong, T. & Bannink, B. (eds) *Attention to Safety* (*Aandacht voor veiligheid* in Dutch) (Klimaat voor Ruimte, 2008); available at <http://www.klimaatvoorruimte.nl>.

Additional information

This article is based on the deliberations and final advice of the Delta Committee (see http://www.deltacommissie.com/en/advies).

Land waters and sea level

Dennis P. Lettenmaier and P. C. D. Milly

Changes in continental water stores, largely human-induced, affect sea level. Better hydrological models and observations could clarify the land's role in sea-level variations.

Understanding the causes of contemporary sea-level rise is a prerequisite for projecting future changes in sea level. The main contributions to the current rise in global mean sea level of about 2 to 3 mm yr^{-1} are thought to come from the loss of land-based ice masses such as ice sheets, ice caps and mountain glaciers, and from the thermal expansion of the oceans[1]. These contributions are sufficient to explain the observed rate of sea-level rise within the uncertainties of the constituent estimates[2]. However, the uncertainties in both contributions are large enough to leave room for a significant additional source of sea-level rise (or, less likely, a sink) that could account for several tenths of a millimetre per year. A number of proposed mechanisms[3] could reduce continental water mass and thereby explain any relatively small missing source of sea-level rise[2]. These mechanisms could also markedly affect any acceleration or deceleration of sea-level rise.

Land loses water

As a simple consequence of mass conservation, the ocean surface rises when the continents lose water. For example, wetland drainage entails deliberate reductions of water storage[4], urbanization can suppress groundwater recharge and thereby lower the water table[5], and extraction of groundwater by pumping (sustainable or not) reduces aquifer storage. Increasingly deeper seasonal thaw of soil above permafrost might promote drainage of the newly activated part of the soil profile[6], which can contain large deposits of ground ice. "Disappearing Arctic lakes"[7] — though contributing little mass on their own — provide evidence that thawing activates drainage pathways at the landscape scale. On the other hand, reduced seasonal freezing of the soil surface could also enhance infiltration of water into soil and increase soil-water storage, particularly where permafrost is absent.

Each of the aforementioned effects could reasonably generate a sea-level change on the order of 0.1 mm yr^{-1}. However, quantitative estimates of the contributions of these mechanisms to rising sea levels are based on speculative global extrapolations of uncertain local observations and data.

Land gains water

One well-defined negative contributor to sea-level rise results from the sequestration of water in man-made surface-water reservoirs (Fig. 1). Near the middle of the twentieth century, the sequestration of water in reservoirs depressed rates of sea-level rise by more than 0.5 mm yr^{-1} on a decadal timescale. More recently, the rate of impoundment of water in reservoirs has slowed (and perhaps, we speculate, has even changed sign). The implied rapid change in the role of reservoirs is a result of two processes: a slow-down in the construction of dams and a gradual infilling of existing reservoirs by sediments, such that their water volume slowly declines. (Reservoir sedimentation affects sea level by the infilling process only if the sequestered sediments would not otherwise have entered the ocean.) One might speculate that increased global interest in water security and renewable energy could cause a temporary resurgence of reservoir construction. However, increased awareness of the negative environmental consequences of dams may also come into play; in any case, many of the best reservoir sites globally have already been developed.

Still other mechanisms might increase water storage on land and thereby marginally suppress rising sea level. The filling of reservoirs might induce a lagged and slow rise in adjacent groundwater storage as a result of reservoir leakage into permeable strata in arid regions, where the water table is initially far below the surface. Similarly, agricultural irrigation in arid environments can cause a long-term increase of water storage[8]. Where irrigation water is obtained locally from a groundwater source, any unevaporated irrigation water is simply moved vertically between land stores, with no net effect on sea level. However, if the irrigation water is taken from a surface supply in a wet region — water that would otherwise have run off into the ocean — then full accounting implies a net sequestration of water on land. Net global changes in groundwater storage associated with reservoir leakage and irrigation, however, are highly uncertain, and any estimates of their magnitude are highly speculative.

Given the foregoing discussion, a bottom-up analysis of global water storage is quantitatively discouraging. Nor do we see promise in the alternative top-down approach — estimation of the net water flux between ocean and land by accounting of precipitation, evapotranspiration and runoff. The flux-accounting strategy would require unachievable measurement precision, because the land contribution to sea-level rise is significantly less than 1% of any of the three water fluxes.

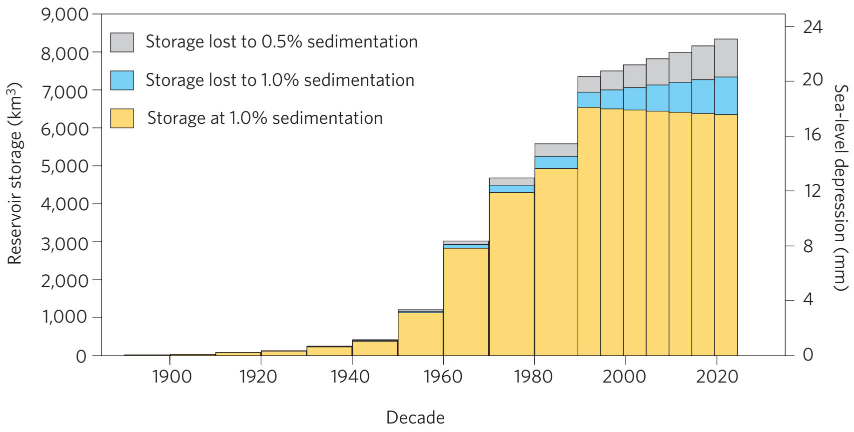

Figure 1 | Accumulated global reservoir water storage 1900–2025. Water storage in reservoirs rose sharply in the mid-twentieth century, but has since slowed down or even reversed in sign when storage losses due to sedimentation (blue and grey bars) are taken into account (1900–2005 from observational data[14]; after 2005 from projections[15]). The data include all reservoirs formed by dams higher than 15 m in height, as well as reservoirs with a capacity of more than 3 million m³ formed by dams 5–15 m in height. The right-hand axis shows implied sea-level depression relative to 1900. The estimated storage losses due to sedimentation[14] (0.5% yr^{-1} and 1.0% yr^{-1}) are adjusted for an assumed sediment porosity of 0.5. Image courtesy of Elizabeth Clark, Univ. Washington.

Weighing the water

Of all available observing systems, satellite gravimetry by the Gravity Recovery and Climate Experiment[9] (GRACE) probably comes closest to providing a direct estimate of temporal variations of total continental water mass. Analysis of the raw GRACE time series (Fig. 2) suggests, if anything, a small tendency towards increasing water storage on land (excluding the ice sheets), implying a (slight) downward trend in sea level attributable to the exchange of water between land and ocean. By contrast, a different analysis of the sea-level rise associated with land-water storage changes[1] suggests a positive rate of 1.3 mm yr^{-1}, with an implied downward trend in average water depth over the global land area (including and dominated by ice caps and glaciers[10]) of −2.5 mm yr^{-1}. We suspect that the absence of a substantial trend in the raw GRACE time series is at least partially explained by two factors: the need to consider a correction for glacial isostatic adjustment[1] and imperfect resolution of the coastline.

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Hoover Dam on the Colorado River, USA. Built in the early 1930s on the border between Nevada and Arizona, Hoover Dam was an early-twentieth-century contributor to the global rise in water storage in reservoirs. Its storage capacity is about 33 km³.

Some opportunities

Estimates of land contributions to sea-level rise have been based primarily on *in situ* observations and other local data that are not readily scalable to the globe. Satellite remote sensing and global modelling offer opportunities for improved tracking of global land-water storage. Appropriate estimates of glacial isostatic adjustment could help GRACE provide more useful constraints on global land-water storage, as could advances in satellite gravimetric methods. Furthermore, satellite altimetry, already useful for the largest lakes globally, holds future promise for inventorying the

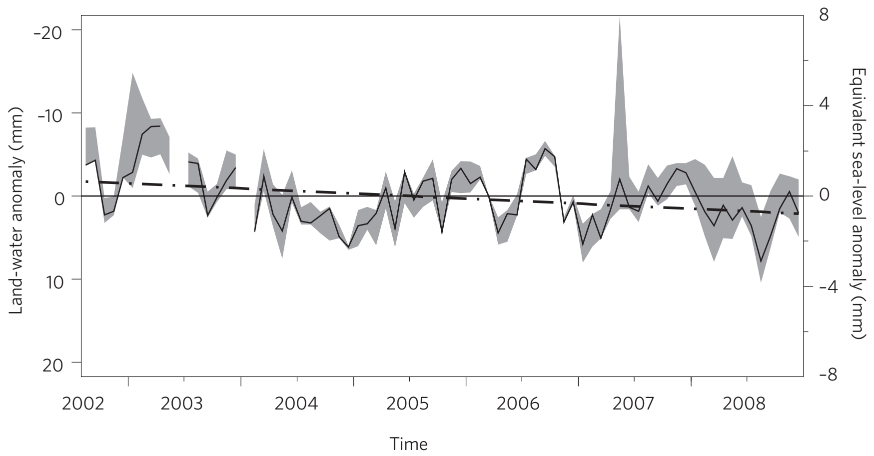

Figure 2 | GRACE equivalent water-depth anomalies (departures from time mean) over the global land area with the exception of Greenland and Antarctica. Land-water storage, according to GRACE, shows very little trend over the limited observational period 2002–2008. Equivalent water-depth anomalies are deseasonalized by subtraction of monthly means, with a fitted linear trend (dashed line). The right-hand axis shows the sea-level anomaly that corresponds to the land equivalent water-depth anomaly. The shading indicates the range of estimates from the Center for Space Research (Univ. Texas, Austin, Texas), GeoForschungsZentrum (Potsdam, Germany) and Jet Propulsion Laboratory (Pasadena, California); the heavy black line is the mean of the three estimates. Image courtesy Huilin Gao, Univ. Washington; GRACE data were processed by D. P. Chambers, supported by the NASA Earth Science REASoN GRACE Project and were extracted from http://grace.jpl.nasa.gov.

contribution of the many small surface-water bodies as well. The Surface Water and Ocean Topography[11] mission proposes to provide measurements of surface-water levels for reservoirs, lakes and wetlands having areas smaller than 1 km^2, to an accuracy within a few centimetres. Combined with estimates of variations in surface-water area, these measurements could allow direct estimates of volume changes in the numerous small water bodies and reservoirs, although reservoir filling by sediments would remain essentially unobservable.

Planned soil moisture missions — the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission and NASA's Soil Moisture Active-Passive (SMAP) mission — are being designed to measure near-surface soil moisture and freeze-thaw status. Although the target domain is a relatively small near-surface water reservoir that cannot contribute much to sea-level rise, these missions, in conjunction with landscape-based hydrological models, could possibly provide a window (albeit quite cloudy) into groundwater in the upper 10 m of the soil.

Changes in the mass of water stored in current permafrost regions could be important, but will probably remain hard to quantify. Improved *in situ* permafrost networks and syntheses combining prospective remote sensing data and improved process models could help to reduce the uncertainty in this term. Similarly, groundwater storage presents a difficult observational challenge. Yet this term could be very important: we suspect that the impacts of many land-use and land-cover changes, such as irrigation, deforestation[12], urbanization and drainage are manifested largely as changes in groundwater storage. It might be possible to estimate water storage in groundwater as a residual from GRACE data, after the surface contributions, along with glacial isostatic adjustment, have been removed. Efforts to explore this approach could be pursued, especially as a complement to ground-based hydrogeological analysis in regions where the expected groundwater signal is large. Such targeted studies might be aided by repeat measurements of surface displacement by interferometric synthetic aperture radar (InSAR), which could also help with estimates of mass loss due to permafrost thaw[13].

A challenge for hydrology

We would find it difficult to refute convincingly, on the basis of observations, the proposition that land, overall, contributes essentially nothing to sea-level rise today. We know that the contribution from at least one individual mechanism (reservoir filling) is large and has changed markedly over the last century, and we are aware of numerous other mechanisms that could possibly be contributing substantially to sea-level rise. Clearly, much work lies ahead if we are to improve on this uncertain situation.

Understanding the land contributions to sea-level rise is just one facet of a more general problem — that of estimating contemporary global hydrological variability and changes, and attributing those changes to human and natural causes. Just as climate scientists use observations and models to assess climate change, hydrologists are now challenged to quantify and explain variations in fluxes and stores of water on the Earth's continents, as influenced by human activities and natural processes. Meeting this challenge might be facilitated not only by the expansion of observations already discussed, but also by the expansion of global hydrological models to represent more natural processes, more human activities and more spatial scales than they do at present. When we more fully use models to integrate available and prospective observations with our understanding of process physics, we can reasonably expect to be rewarded with a better understanding of continental-scale hydrology, including its impact on global sea level. ❐

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References

1. Cazenave, A. *et al. Glob. Planet. Change* **65,** 83–88 (2009).
2. Bindoff, N. L. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon S. *et al.*) (Cambridge Univ. Press, 2007).
3. Milly, P. C. D. *et al.* in *Understanding Sea-level Rise and Variability* (eds. Church, J. A., Woodworth, P. L., Aarup, T. & Wilson, W. S.) (Blackwell, in the press).
4. Zedler, J. B. & Kercher, S. *Annu. Rev. Environ. Resour.* **30,** 29–74 (2005).
5. Small, S. *Earth Interactions* **8,** 1–18 (2004).
6. Berezovskaya, S., Yang, D. & Kane, D. *Geophys. Res. Lett.* **31,** L21502 (2004).
7. Smith, L. C., Sheng, Y., MacDonald, G. M. & Hinzman, L. D. *Science* **308,** 1429 (2005).
8. Wisser, D. *et al. Geophys. Res. Lett.* **35,** L24408 (2008).
9. Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F. & Watkins, M. *Science* **305,** 503–505 (2004).
10. Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F. & Ohmura, A. *Geophys. Res. Lett.* **33,** L19501 (2006).
11. Alsdorf, D. E., Rodriguez, E. & Lettenmaier, D. P. *Rev. Geophys.* **45,** RG2002 (2007).
12. Grainger, A. *Proc. Natl Acad. Sci. USA* **105,** 818–823 (2008).
13. Galloway, D. L., Jones, D. R. & Ingebritsen, S. E. *US Geological Survey Fact Sheet-051-00* (2000).
14. White, W. R. *World Water Storage in Man-Made Reservoirs* (Foundation for Water Research Publication FR/R0012, 2005).
15. Rosegrant, M. W. & Cai, X. M. *Water Int.* **27,** 170–182 (2002).