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Water management challenges associated with mining projects in Greenland

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Abstract

Following the establishment of self-government in 2009, Greenland undertook significant steps to expedite the development of a substantive mining industry based on known and inferred resource deposits. While the recent downturn in global commodity prices has suppressed the development of new mining projects in Greenland, large-scale projects are still anticipated within the next decade, owing to long-term increases in the demand for metals and rare earth elements.

The development and operation of pro-glacial mining projects, situated directly adjacent to the Greenland Ice Sheet, pose unprecedented challenges for mine water management. Specific meltwater runoff regularly exceeds 1 m per month in the melt zone of the low elevation ice sheet periphery. In order to minimize water treatment costs, ice sheet runoff should ideally be captured and diverted upstream of pro-glacial mining projects, before reaching developed areas. Complex sub-, supra- and en-glacial water flow, however, contribute to major spatial variability in ice sheet runoff, while climatic forcing contributes to major temporal variability in ice sheet runoff. Additionally, ice movement results in significant challenges that must be addressed when designing an on-ice sheet water management system.

We examine the magnitude and breadth of these challenges in the context of a proposed open ice pit mining project that infringes on the southwest margin of the ice sheet. Using state-of-the-art regional climate model output, forced by re-analyzed climate data, we assess characteristic mean monthly meltwater runoff both within the ice sheet catchment and upstream of the pro-glacial mine site. This assessment not only provides insight into the water management requirements of pro-glacial mines, but also provides a broader water management context in which to examine the hazard associated with catastrophic drainage of Greenland supra-glacial lakes.

Introduction

Increasing global demand in resources, improvements in mining and prospecting techniques, and changes in regulatory conditions are making mining in Arctic regions economically feasible (Colgan and Arenson, 2013). Additionally, rapid and ongoing warming of the Arctic in recent decades (Qinghua et al., 2014) has resulted in significant glacier retreat and sea-ice reduction. These cryospheric changes are essential for improved economic feasibility and resource access and distribution. Greenland, which achieved Self-Government in 2009, has undertaken significant steps to expedite the development of a mining industry based on known and inferred resource deposits. Given that over 80 % of Greenland is covered by either glaciers or ice sheet, several proposed Greenland mining projects are set to occur in, or will be influenced by, glacial/pro-glacial settings, whereby mining activities occur immediately adjacent to an ice margin. These include the Isukasia iron prospect, the Kvanefjeld uranium prospect, the Malmbjerg molybdenum prospect, and the potential Maarmorilik lead/zinc mine expansion (Figure 1). Other resources, including gold and gems, are also present in Greenland, and may likely also be mined in the future. A myriad of unique environmental, geotechnical and ice-mechanics challenges are associated with glacial/pro-glacial mining operations, including: supra-glacial meltwater runoff, en- and sub-glacial water flow, excavating glacier ice overburden, phase changes during the transportation of ice muck, and maintaining supraglacial access roads (Colgan and Arenson, 2013). In this paper, we focus on the unique engineering management challenge of extreme ice sheet meltwater runoff at the Isukasia (or Isua) prospect in Southwest Greenland, approximately 100 km northeast of Nuuk, Greenland. The purpose of this assessment is to underline order-of-magnitude differences in the water management required for projects located in pro-glacial settings, relative to conventional mine settings.

Figure 1: Location, and primary minerals, of Greenland mining prospects located in pro-glacial settings (i.e. directly adjacent to an ice margin). Glacier and ice sheet extent from Citterio and Ahlstrøm (2013)

Method

Here, we describe how we calculate lower and upper bounds for the ice sheet meltwater runoff potentially reaching the Isua prospect. Following a confidence bound approach, we delineate both lower and upper limit ice sheet catchment areas. The lower limit catchment area was delineated following the approach of van As et al. (2014), which employs RADARSAT-derived ice surface movement vectors (Joughin et al., 2010). This surface velocity approach assumes that the direction of water flow reflects the direction of ice flow, both of which are governed by gravitational driving stress and sub-glacial bedrock topography. The upper limit catchment area was delineated following the approach of Rennermalm et al. (2013), which employs an altimetry-derived ice surface elevation model. For this assessment the ASTER GDEM v2 digital elevation model was utilized, which has a 1 × 1 arc-sec tile raster resolution (Tachikawa et al., 2011). This surface elevation approach uses a conventional terrestrial surface water routing algorithm, whereby water is assumed to flow on the ice sheet surface and follow topographic divides. The local catchment just north of the Isua prospect was slightly modified to be consistent with in situ observations of supra-glacial streams breaching a local topographic divide. The lower limit (minimum) ice sheet catchment, which has an area of $7.50 \cdot 10^8$ m^2, extends ~100 km inland from the Isua site with approximately uniform width. The upper limit (maximum) ice sheet catchment, which has an area of $6.32 \cdot 10^9$ m^2, increases in width with distance inland from the Isua site (Figure 2).

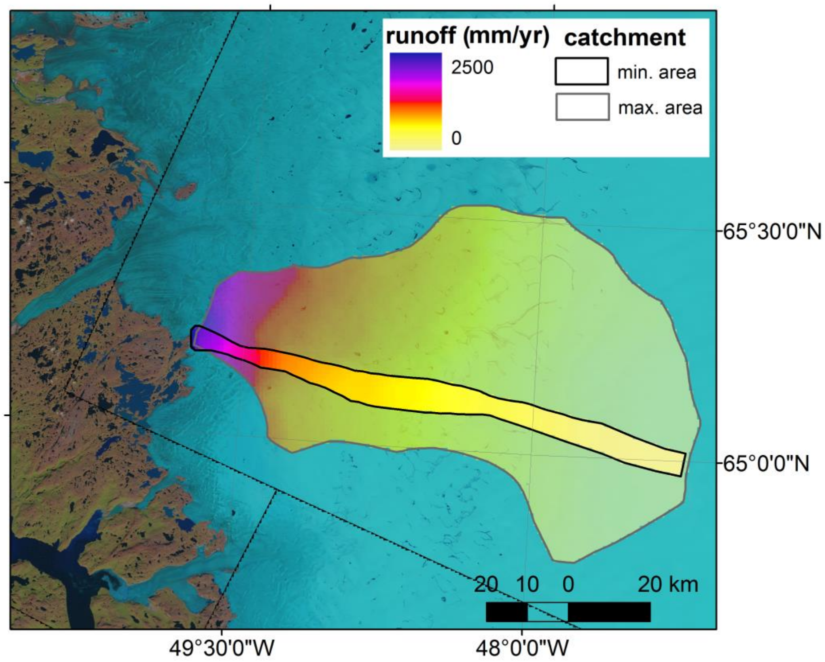

Figure 2: Delineation of the minimum and maximum plausible Isua prospect supra-glacial ice sheet catchments. Shading denotes mean annual meltwater runoff over the 2004 to 2013 decade as simulated by the MAR (v3) regional climate model forced by ERA-Interim reanalysis data. Background image source: Landsat 8

The minimum and maximum runoff within the catchments were quantified using the monthly runoff fields simulated by the regional climate model MAR (Version 3) over the 2003 to 2014 decade. The MARv3 model is forced by ERA-interim reanalyzed six-hourly climate data at its lateral boundaries, as well as six-hourly sea surface temperature and sea ice cover within its domain (Dee et al., 2011; Fettweis et al., 2013). A bilinear interpolation was employed to downscale simulated monthly runoff fields from their native 15 km MARv3 resolution to 1 km spatial resolution employed in this assessment. Runoff fields within the minimum and maximum catchment areas were then spatially integrated to assess lower and upper limits for the range of total runoff potentially reaching the Isua prospect in each month during the 2003 to 2014 decade (Figure 3). The influence of climate variability on monthly runoff variability was quantified as the standard deviation in runoff during each month of the year over the study decade. For this assessment it was conservatively assumed that MARv3 has an analogous 1σ uncertainty of ~ 15 % associated with model accuracy in simulating each component of surface mass balance, including runoff. We note that we use the MARv3 “runoff” component of “surface mass balance”, which is the portion of “melt” that actually leaves the ice sheet. In the ice sheet accumulation area, a substantial fraction of melt can be retained by refreezing in the porous near surface firn layer.

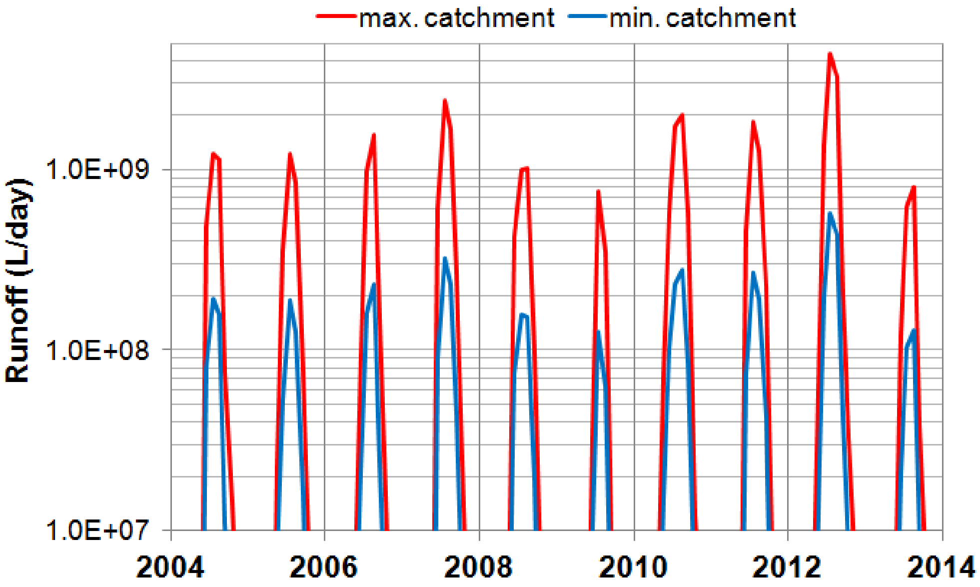

Figure 3: Monthly meltwater runoff, simulated by the regional climate model MAR (v3) forced by ERA-Interim reanalysis data, within the minimum and maximum Isua prospect catchment areas over the 2003 to 2014 decade

The three main independent sources of uncertainty in the monthly runoff estimate are basin delineation, climatic variability, and model accuracy. These were combined via a Monte Carlo simulation to assess the cumulative uncertainty. In this uncertainty propagation, the uncertainty due to basin delineation is assumed to be a uniform distribution between the runoff associated with the minimum and maximum catchment areas. The uncertainties due to climatic variability and model accuracy are assumed to be normally distributed with the 1σ variances listed in Table 1. Randomly sampling from these three uncertainty distributions in 10,000 simulations permits probability density functions to be estimated for the ice sheet meltwater runoff potentially reaching the Isua prospect site in each month of the year. As these probability density functions represent cumulative uncertainty associated with the three main independent sources of uncertainty, the 95 % (or 2σ) confidence level upper limit may be interpreted as the absolute magnitude of runoff potentially reaching the Isua prospect in each month of the year (Figure 4). The 95 % confidence level lower limit, for which the Mont Carlo uncertainty propagation returns negative values in most months, was disregarded; the potential upper limit for ice sheet runoff is the more relevant water management criterion.

Table 1: The 95 % (or 2σ) confidence level upper limit for the runoff potentially reaching the Isua prospect in each month of the year over the 2003 to 2014 decade, as well as the three main sources of uncertainty: (1) the absolute uncertainty range associated with the delineation of the ice sheet runoff catchment, and the relative 1σ variance due to both (2) climatic and melt intensity variability over the study decade and (3) assumed accuracy of simulated runoff in the MAR (v3) regional climate model forced by ERA-Interim reanalysis data

Month	Runoff 2σ upper limit (L/d)	Catchment delineation range (L/d)	Climatic variability (%)	Model accuracy (%)
January	$1.6 \cdot 10^6$	2.8 to $9.9 \cdot 10^5$	46	15
February	$1.4 \cdot 10^6$	2.2 to $8.0 \cdot 10^5$	58	15
March	$9.7 \cdot 10^5$	1.2 to $4.0 \cdot 10^5$	104	15
April	$3.4 \cdot 10^6$	0.34 to $1.0 \cdot 10^6$	178	15
May	$4.3 \cdot 10^7$	0.32 to $1.3 \cdot 10^7$	172	15
June	$9.3 \cdot 10^8$	0.72 to $4.5 \cdot 10^8$	84	15
July	$3.0 \cdot 10^9$	0.23 to $1.6 \cdot 10^9$	69	15
August	$2.4 \cdot 10^9$	0.20 to $1.4 \cdot 10^9$	59	15
September	$3.6 \cdot 10^8$	0.29 to $1.7 \cdot 10^8$	96	15
October	$3.7 \cdot 10^7$	0.20 to $1.1 \cdot 10^7$	77	15
November	$7.6 \cdot 10^6$	0.63 to $2.3 \cdot 10^6$	62	15
December	$5.9 \cdot 10^6$	0.41 to $1.5 \cdot 10^6$	74	15

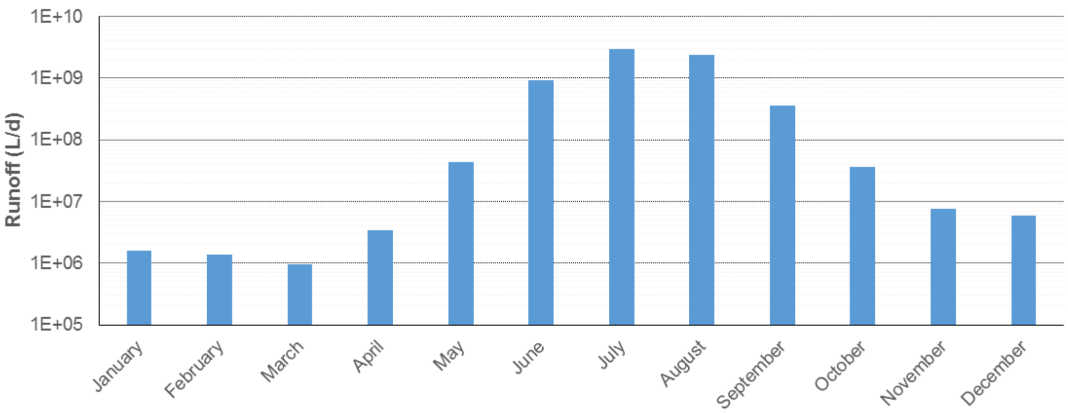

Figure 4: The 95 % (or 2σ) confidence level upper limit for the runoff potentially reaching the Isua prospect in each month of the year over the 2003 to 2014 decade

Assessment

In the immediate vicinity of the Isua prospect, mean annual specific runoff approaches 3,000 mm water equivalent per year and per unit area (Figure 1). Within the minimum catchment area, the mean annual ice sheet runoff was $4.45 \cdot 10^{11}$ L/a over the 2003 to 2014 study decade. Within the maximum catchment area, the analogous runoff was $3.38 \cdot 10^{12}$ L/a. Thus, uncertainty in mean annual runoff due to catchment delineation spans about an order of magnitude. The vast majority of annual runoff occurs during the brief four month period between June and September (Table 1; Figure 4). Earlier in the melt season, the presence of an appreciable snowpack temporarily absorbs melt, and suppresses runoff through May.

Over the study decade, of the four peak melt months, relative variability in monthly runoff due to climate variability is greatest in September, with a 1σ standard deviation of 96 %. This large climate-induced variability in September runoff is a direct consequence of variability in melt season length. As demonstrated by the Monte Carlo cumulative uncertainty propagation, however, despite the relatively large climatic variability in September, the absolute uncertainty in monthly runoff in September is smallest of the four peak runoff months (Figure 5). In each of the four peak runoff months the probability density functions are positively skewed. This is a result of the normally distributed uncertainties due to climatic variability and model accuracy being dependent on the uniformly distributed uncertainty due to catchment delineation. This may be regarded as a reasonable characterization of extreme events.

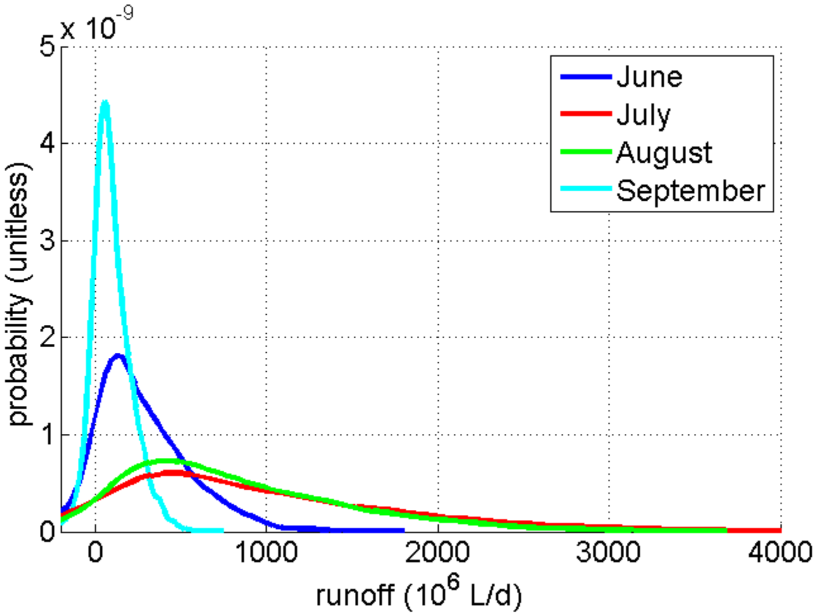

Figure 5: Probability density functions of monthly ice sheet meltwater runoff potentially reaching the Isua prospect during the four peak runoff months

Taking the three main sources of uncertainty into consideration (basin delineation, climatic variability, and model accuracy), the monthly probability density functions assess the highest 95 % (or 2σ) confidence level upper limit for the absolute magnitude of runoff potentially reaching the Isua prospect in July and August, approximately $2.8 \cdot 10^9$ L/d (Table 1; Figure 4). This is equivalent to approximately 44 t/s of water flow. While this potential site inflow rate is large in the context of conventional mine water management, it is small in the context of the present rate of ice loss from entire ice sheet due to climate change, which is approximately 8,300 t/s when averaged over a year (Andersen et al., 2015).

In 2012, London Mining Plc, the initial developer of the Isua site, presented a water balance for the project as part of the pre-feasibility study (BFS, 2012; London Mining, 2012). In this water balance, the flow into the open pit was estimated as $7.8 \cdot 10^6$ m^3/a, with no specified uncertainty range. Assuming a 60-day melt season, this is equivalent to an average site inflow of $1.3 \cdot 10^8$ L/d. This developer estimate is therefore an order-of-magnitude lower than the upper limit confidence bound assessed here. We note, however, that the initial developer estimate did not consider multiple compounding sources of uncertainty, and is thus not directly comparable to the values presented here. Both estimates agree, however, that the design of a water management plan for the Isua prospect should be compatible with site inflow rates in the range of 10^8 to 10^9 L/d.

Discussion

Subglacial water flow

The assessment presented here focuses on the ice sheet runoff potentially reaching the Isua prospect. It is important to bear in mind, however, that the vast majority of meltwater runoff produced on the ice sheet surface enters the en- and sub-glacial networks prior to surficial discharge at the ice sheet margin (Smith et al., in press). This provides a strong impetus to understand the preferential sub-glacial drainage routes in the vicinity of any given glacial/pro-glacial site. We would contend that the delineation of minimum and maximum catchment areas using independent approaches bounds the uncertainty in runoff associated with en- and sub-glacial flow. Unlike groundwater flow through rock or sediments, however, the transmissivity of sub-glacial water flow can change rapidly, on the order of hours to days, in response to not only frictional melting along conduit walls, but also conduit opening or closing due to viscous creep (Colgan et al., 2011). Meltwater delivery to the sub-glacial hydrologic network is also influenced by catastrophic supraglacial lake drainage events, whereby large volumes of meltwater (on the order of 10^9 liters) are delivered to the sub-glacial hydrologic network via crevasse hydrofracture (e.g., Liang et al., 2012). A single catastrophic lake drainage within the Isua prospect ice sheet catchment could briefly double peak melt season site inflow rates. In regional climate models, ice sheet runoff is simulated without any parameterization, or allowance, for en- or sub-glacial hydrologic processes, including highly transient transmissivity and catastrophic events (Fettweis et al., 2013). Thus, while our confidence bound approach constrains the spatial uncertainty influencing runoff magnitude, it does not constrain the temporal uncertainty due to catastrophic events in the runoff reaching a glacial/pro-glacial site.

Minimizing contact water

With all mine water management systems, the main goal is to limit the volume of contact water and maximize water diversion around any infrastructure, to keep it within a non-contact water system. The upper limit determined in our assessment is a flow of 44 t/s, which may even be briefly exceeded during sudden supra-glacial lake drainage events. Based on our present understanding, there is no single open pit mining project in operation that manages water volumes and peak inflows as great as within the confidence range we present here. As such, it is imperative to explore unique glacier engineering solutions for reducing contact water to a manageable amount pro-glacial sites like the Isua prospect. The major challenge is capturing and diverting ice sheet runoff on, in, or immediately below, the ice sheet, when neither the ice nor its water channels are stable, but rather highly transient. High maintenance solutions are therefore unavoidable, which may result in particular challenges during mine closure. In parallel, solutions could be implemented into the water management system that dampen peak flow to the water treatment plant. The use of large reservoirs, such as proposed by London Mining Plc (BFS, 2012; London Mining, 2012), does permit the temporarily capture of peak inflow during the peak melt months of July and August, as well as the in parallel treatment of contact water throughout the whole year.

Climate change

Climate change will exacerbate the already unique challenges associated with managing extreme volumes of ice sheet runoff at glacial/pro-glacial resource development sites like the Isua prospect. Increased atmospheric temperatures are expected to increase the ice sheet runoff by a factor of approximately five by the end of this century (Fettweis et al., 2013). As the probability of catastrophic supraglacial lake drainages into the sub-glacial hydrologic network is proportional to this summer melt intensity (Liang et al., 2012), an increase in ice sheet runoff within the Isua ice sheet catchment will most likely result in an increase in catastrophic lake drainage events within the catchment.

Summary and conclusions

Greenland has undertaken significant steps to expedite the development of a mining industry with large scale projects anticipated to start within the next decade. Developing and operating large scale mining projects adjacent, or nearby, to the Greenland Ice Sheet poses unprecedented challenges for mine water management. Not only are the anticipated ice sheet runoff rates challenging to manage, but conducting a proper geotechnical assessment is difficult due to the sheer scale of required data. In contrast to non-glacierized catchments, supra-glacial topography may not be representative of either supra-, en- or sub-glacial water flow direction. In addition, glaciers are dynamic so that these channels may change during the operation of a project, but also in closure stages either naturally or influenced by the operation. Finally, catastrophic supra-glacial lake drainage events may significantly increase runoff for short periods.

The monthly magnitude and variability of ice sheet meltwater runoff was determined for the proposed Isua iron ore open pit mining project, which infringes on the Southwest margin of the Greenland Ice Sheet. We employed ice sheet runoff fields simulated by state-of-the-art regional climate modelling forced by re-analyzed climate data. The assessment showed that the absolute magnitude of ice sheet runoff potentially reaching the Isua prospect in July and August is approximately $2.8 \bullet 10^9$ L/d, which is equivalent to a site inflow of 44 t/s. The site inflow rates are nearly an order-of-magnitude different when employing the lower and upper ice sheet catchment areas. Regardless of employing the lower or upper catchment area, the management of such site inflow volumes is extremely challenging.

In order to minimize water treatment costs, significant portions of the runoff should be captured and diverted upstream, before reaching any developed areas and becoming contact water that must be treated. Surface water could be intercepted on the ice sheet surface using trenches or ice berms constructed on upstream of the open ice pit. Meltwater from the surface of the excavated ice pit slope, which may still be considered as non-contact water depending on regulations, may be collected at the glacier bed, just beyond the toe of the excavated ice face, via a water collection system and diversion berm. Water from existing supra-glacial channels could be diverted using a combination of sumps and heat-traced pumps and pipelines. However, the existence of moulins or en- and sub-glacial channels is only poorly understood at best. Culverts or temporary access bridges may be used when access roads on the ice have to cross major supra-glacial creeks on the ice. Adjustable and flexible bridges can accommodate seasonal changes in the supra-glacial runoff channels and the ice movement better than culverts. Managing water for glacial/pro-glacial mining projects is very challenging due to the huge volumes of runoff and the extreme seasonal variability that must be anticipated. It appears to be easy to underestimate the plausible upper limit of monthly runoff, which should inform the key design criterion of a mine's water management system. A good monitoring system, ideally initiated prior to site development, can significantly reduce the uncertainties in a site inflow assessment, and provide valuable baseline data for the validation of a water balance model. Overall, however, hydrologic variability and climate change will always require major maintenance and contingency measures to be implemented through adaptive engineering.

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