Title: An Economic Impact Assessment of the Use of Earth Observation Information in Flood Hazard Communication

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Funding: The research for this analysis was supported by NASA Grant NNX17AD72G.

Acknowledgements: The authors thank Craig Broadbent BYU-Idaho for suggesting the nonparametric Mann-Whitney test for whether the two sample means of the flood forecast empirical adjustments are equal. The authors appreciate the North Central River Forecast Center personnel for conducting retrospective model runs and producing the associated figure.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Author Contributions: All authors contributed to the study design and implementation. All authors read and approved the final manuscript.

Abstract

Flood hazard forecasts are critical information to reduce the impacts of a disaster. Improved operational forecasts can lead to timelier decisions, which translates into more cost-effective pre-flood mitigation decisions. In this paper, we quantify this economic value of an improved forecast for two types of independent empirical adjustments to National Weather Service Ensemble Streamflow Prediction (ESP). The North Central River Forecast Center (NCRFC) adjusts the ESP to produce an operational seasonal river discharge forecast with forecaster intervention and complements the forecast with an experimental empirical soil moisture adjustment from the Gravity Recovery and Climate Experiment (GRACE). In a retrospective case study, we apply the complementary NCFRC + GRACE forecast to increase the confidence in implementing flood mitigation earlier in flood hazard planning. Specifically, we focus on the reforecast of the 2011 spring season for the Sheyenne River in North Dakota and find that flood protection decisions in Valley City, ND could have been made 5 days earlier and mitigation costs could have been reduced by $1.7 million.

Keywords: Flood forecasting, Earth observation, Hazard warning, Cost effectiveness,

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1 Introduction

The societal costs of flooding have increased in the United States over the last several decades as more people and property locate in harm's way (Davenport et al. 2021, Pielke and Downton 2000). Some of these costs are associated with community preparation for potential floods, which must be balanced against the value of damages that are expected to be avoided from community preparation should a flood take place. Decisions surrounding community preparation are, in turn, driven by different forms of flood hazard information. For example, decisionmakers may use river discharge forecasts to determine the extent and timing of expenditures that reduce flood risk. Thus, improved flood hazard information can generate socioeconomic benefits by helping communities achieve a more cost-effective balance between meeting damage avoidance objectives and undertaking costly mitigation actions. The case study is conducted using a severe flood that occurred in spring of 2011 to study the potential benefit of a consolidated message to communicate timely, accurate hazard information for pre-flood mitigation actions. Damages from the 2011 flood convinced stakeholders in Valley City, ND to pursue permanent flood protection (North Dakota State Water Commission 2019), making it a particularly salient case for studying the economic impacts of different approaches to flood forecast.

In this paper, we present a framework based on information theory to: (1) Quantify the value of new data products in flood hazard communications, and (2) Estimate the value of a new data product (GRACE), which has not been done before in the flood hazard communication context. Specifically, if the probability of water flow exceeds a community determined hazard threshold, a decision is made to undertake pre-flood mitigation *(Schueneman 2011)*. As the forecasted flood severity increases, protection will require decisions to invest more resources to attain damage avoidance objectives, and in turn impose greater mitigation costs on communities. Moreover, there is a tradeoff between forecast accuracy and forecast timeliness; forecasts become more accurate as the forecasting period shortens (e.g., a 7-day forecast vs. a 1-month forecast), but longer forecasting periods give decisionmakers more time to implement mitigation actions, with potential associated cost savings (Lawrence 1999). We estimate the monetary savings derived from the integration of NASA Gravity Recovery and Climate Experiment soil moisture information into the National Weather Service operational flood forecast. The socioeconomic benefits estimated in our framework are thus based on the value of forecast timeliness—that is, earlier hazard communications with the equivalent accuracy are beneficial because they allow for earlier community preparation.

Our analysis is based on the Community Hydrologic Prediction System (CHPS), which houses a probabilistic suite of models that was developed by the National Weather Service (NWS) to assist communities to respond effectively to flood risk (NOAA 2019, Restrepo 2017). Forecasting products like CHPS rely on many sources of information about past and current hydrologic conditions. Furthermore, new sources of data such as communication with local forecasters and remotely sensed indicators can be added as post-processed empirical adjustments. The value of the information used for an adjustment is positive if decisions based on CHPS with the adjustment, relative to the case in which decisions are based on CHPS without the adjustment, lead to reductions in societal losses from flooding that exceed any additional costs associated with community preparation.

Herein we assess the value of adjusting an operational flood forecast by using a soil moisture analysis that incorporates the NASA Gravity Recovery and Climate Experiment data assimilation system (GRACE-DA). GRACE-DA is a research-grade system that combines terrestrial water storage estimates from the GRACE satellite mission with a physically based land surface model to generate gridded estimates of hydrological states and fluxes. Earlier efforts in which GRACE-DA has been applied was to monitor the severity of droughts as an input to the US Drought Monitor, the analysis in that application focused on a long duration event that had regional impacts rather than a seasonal flooding episode (Bernknopf et al 2018). More generally, our study adds to the literature on economic impact assessments of Earth observation-based services and tools applied to other decision contexts such as water resource management (Stroming et al. 2020), wildfire assessment (Bernknopf et al. 2020), and public health (Borowitz et al. 2023, Pakhtigian et al. 2024).

We use a Bayesian decision framework (Economu et al. 2016) to evaluate the economic benefits of adding the signal from a GRACE-DA soil moisture estimate to CHPS as a complementary input into an operational forecast. We conduct a case study in the Sheyenne River subbasin in North Dakota, shown in Figure 1, to assess whether an operational river stage forecast is improved by constructing a consolidated reforecast incorporating GRACE-DA information and quantify the economic benefits of the improved forecast.

Figure 1. Sheyenne River sub-basins and USGS gaging stations. Site location data from Water Quality Portal (https://www.waterqualitydata.us/provider/NWIS/USGS-ND/).

The remainder of the paper is organized as follows. The next section describes the decision context for our benefits assessment and presents an economic model of the benefits of natural hazard damage reduction and public sector responsibilities linked to natural hazard and risk communications. The third section describes a conceptual framework for linking data for flood hazard forecasts to public information dissemination and, ultimately, socioeconomic value. The concept of an information structure is introduced and explained in the application of floods as a mapping of scientific data into a measurable space of signals and messages that translates physical measurement of flood stage hazard from a state of nature to a probability (Lawrence 1999). The fifth section describes an economic analysis of the value of a consolidated NCRFC + GRACE-DA adjusted forecast to reduce delay in mitigative actions, informed by an experimental reforecast of the 2011 flood in Valley City, ND and decisions made regarding community assets and infrastructure. The case study is followed by discussion and conclusion sections.

2 Background

2.1 Decision context

Flood warning systems research was initiated in the late 1960s by the US Army Corps of Engineers (USACE) New York District (Porter et al. 2011). USACE concluded that a 48-hour advanced warning could reduce riverine flood damage in the Passaic River Basin in New Jersey by up to 35 percent. Models were initially deterministic. Deterministic models provide a single realization of a simulated process and use this single realization to derive any required design, planning, or management products. Deterministic hydrologic models are likely to produce model outputs with lower variance than experienced (Farmer and Vogel 2016).

Currently, public sector responsibilities and availability of climatological and meteorological data dictate what methods and models are inputs to an operational forecast. Responsibility for inland flood hazard and risk communication has been entrusted to NWS and USACE. NWS issues warnings and other risk communications that involve potential high volume river discharges (Pappenberger et al. 2015) and for delivering flood hazard information to the entire United States (Roe et al. 2007 and NOAA 2019). NWS defines stages for multiple flood severity levels, including: Bankfull/Action Stage represents when action is taken for possible high water. Water may cause minor impacts and be a nuisance to persons near the stream. Local governments or agencies may take actions to reduce property damage and danger to life. Minor Flood Stage represents the level some property flooding and public threat may occur. Roadways, trails, park land, and private property near the stream may become flooded; that creates a hazard to lives, property, or commerce. Moderate Flood Stage represents a level such that flooding of structures and main roadways may occur. Residences and numerous roadways near the stream may become flooded, creating disruptions to daily life. Evacuations may be necessary. Major Flood Stage represents extensive flooding of structures, main roadways, and other flooding of critical infrastructure may occur. Schools, hospitals, police stations, fire stations, residences, businesses, and roadways may become flooded. Evacuations may be necessary, and significant disruptions to daily life could be anticipated (https://www.weather.gov/lot/hydrology_definitions). The issuance of flood advisories or warnings is linked to Flood Stage (NWS 2021). Both Moderate and Major Flooding Stage are associated with the issuing of flood warnings.

Communities depend on accurate river discharge estimates and flood forecasts from the NCRFC for minimizing hazard risk in the central US. The NCRFC covers parts of nine states and a small portion of Canada, spanning an area of about 350,000 mi^2. It includes portions of three major watersheds: the Mississippi River Basin, the western portion of the Great Lakes Basin, and Hudson Bay (the area of interest for this study). Although NCRFC river flow forecasts are issued routinely in many locations to support activities such as navigation and hydropower, forecasts at additional designated forecast points are issued when rivers exceed or are forecast to exceed a stage threshold known as the "forecast issuance stage," which for most forecast locations is the "bankfull" or "action stage" as defined in the federal responsibilities.

The USACE risk assessments mandate flood emergency action plans and risk management decisions that pertain to dams and levee systems (USACE 2020). In "A Guide to Public Alerts and Warnings for Dams and Levee Emergencies," USACE outlines the required contents for communication through an alert and warning (USACE 2019). This document points out the different roles that USACE and NWS play in flood hazard and risk communication. In contrast to NWS flood severity levels, USACE hazard communications are defined as Alert, Watch, and Warning.

2.2 Flood hazard estimation

An operational river discharge forecast is comprised of a series of steps that is initiated with historical data and physical process models that are transformed into a seasonal river discharge forecast. The framework to produce a forecast requires interaction between a forecaster and a suite of models, leading to adjustments that reconcile differences between model predictions and post-modeling updates with empirical observations to improve flood forecasts (Restrepo 2017). An adjusted forecast is meant to decrease the uncertainty associated with the timing and severity of a flood. An NCRFC river flood stage s forecast $FS(s;t)$, where $s = 0,1,\dots,4$, for 0 = Normal Pool, 1 = Action Stage, 2 = Minor Flood Stage, 3 = Moderate Flood Stage, and 4 = Major Flood Stage, and $t = 1,\dots,T$ indexes the time period of the forecast that is communicated as a probability of exceeding a river discharge rate (Restrepo 2017).

CHPS includes models that comprise the Ensemble Streamflow Prediction (ESP) System, which is a seasonal probabilistic hydrologic forecast that utilizes historical precipitation data as input to the NCRFC hydrologic forecast. When the historical precipitation of individual observation years is applied to the current model state (especially soil moisture and snowpack), a conditional ensemble of model runs is produced. The conditional ensemble can then be compared to the historical, streamflow-based probabilities of exceedance, providing a contextual look at how the current conditions compare to other years during the same season. These long-range forecasts provide information on future river stage, flow, and/or volume. Minimally, a forecast is issued at the end of a month for the upcoming three-month period that shows how current conditions impact the likelihood of a significant flooding event.[1] CHPS integrates frequent empirical observations to update modeled river discharge rates and deliver an operational forecast of water flows to government agencies and other stakeholders. The NCRFC conceptual model for soil water storage is based on the Sacramento Soil Moisture Accounting Model (SAC-SMA) that is applied with an amount of water to enter the hydrologic system, either via rain or snowmelt. The SAC-SMA is the precipitation/runoff model used by the NCRFC to generate river forecasts. In the SAC-SMA, rainfall is partitioned into surface runoff and infiltration that is governed by the upper zone soil moisture states and the percolation rate into a lower zone, and model calibration is based on river response under different flow regimes (Loren et al. 2007). Manual model calibration is carried out periodically at NCRFC by hydrologists who are experts on the subbasins if/when unmodified streamflow simulations systematically drift from newer observations.

GRACE-DA assimilates GRACE satellite observations (Tapley et al. 2004) of terrestrial water storage anomalies into an advanced Land Surface Model (LSM) to improve model simulation of terrestrial water storage and associated hydrological fluxes. The version of GRACE-DA used here assimilates GRACE-derived monthly terrestrial water storage anomalies to the NASA Catchment Land Surface Model (CLSM). It has been implemented for CONUS (Zaitchik et al. 2008; Houborg et al. 2012; Kumar et al. 2016) and global extents (Li et al. 2019). The model is forced by high resolution, observation- and atmospheric analysis-based meteorological data, and it also incorporates high resolution soil, vegetation, and topographic information. Together with the ensemble Kalman smoother data assimilation scheme, these high-resolution inputs enable the model to downscale the monthly, coarse resolution (effectively about 150,000 km^2 at mid-latitudes) GRACE observations to produce daily or better output on the model's 0.125° grid. GRACE-DA simulations, then, integrate information from meteorological data, landscape parameters, model physics, and GRACE observations. In this study we do not attempt to disentangle the contribution of each to the quality of the simulation. GRACE-DA outputs include the states and fluxes of the land surface water and energy balances.

Working with NCRFC forecasters, we examined forecasts with and without GRACE-DA adjustments. We focus on the severe flood that occurred in spring of 2011 and use it to study the potential benefit of a consolidated message to

[1] https://www.weather.gov/media/serfc/EnsemblesfactsheetESP.pdf.

communicate timely, accurate hazard information for pre-flood mitigation actions. Damages from the 2011 flood convinced stakeholders in Valley City, ND to pursue permanent flood protection (North Dakota State Water Commission 2019), making it a particularly salient case for studying the economic impacts of different approaches to flood forecasts.

The event also is convenient for our analysis because the GRACE-informed soil moisture and groundwater indicators were, in this case, an improvement relative to CHPS. This allows us to use the 2011 flood as a test case of a good forecast. We emphasize that our results are not a claim that the GRACE-DA system, as currently implemented for CONUS, offers consistent or reliable benefit for this river basin. In fact, when we looked at other years with more moderate flooding (2004, 2009, 2010, and 2013) we found that GRACE-DA performance relative to CHPS was decidedly mixed. This clearly indicates that the present GRACE-DA system, which is a national-scale application that has not been evaluated or optimized for application to this basin, would require further development to maximize its value for the region.

2.3 Economic benefits of improved forecasts

When the NCRFC receives data updates, it is diligent in revising the forecast to improve the effectiveness of the planned response. However, there is remaining uncertainty in the forecast that can lead to losses from inefficient timing of proactive mitigation actions. Once the warning is issued, uncertainty in the forecast can result in having to pay for damages after an event occurs or incurring unnecessary pre flood mitigation costs.

River discharge forecasts are often used to determine temporary actions such as the pre-flood installation of clay levees, sandbags, and Hesco barriers.[2] If the expected probability of a major flood is high for a particular flood event, adjustments that generate a forecast with a longer lead time allow communities to save resources that would otherwise be used for unexpected changes in mitigation plans. For example, delaying action results in the community rushing to install levees and barriers that cost more due to less advance notice and greater materials and labor costs. By avoiding this type of implementation delay, a timely verified forecast yields monetary savings. In

[2] A Hesco barrier is a flood control measure that is a steel wire crate lined with a plastic canvas and then filled with dirt to form a wall of protection. https://archive.kpcc.org/news/2016/01/11/56742/army-corps-to-shore-up-la-river-with-hesco-barrier/

what follows, we compare actions taken with and without an augmented information structure that includes the current CHPS forecast and independent GRACE-DA soil moisture data.

3 Model framework

3.1 Data for flood hazard forecasts

The data input for a CHPS flood forecast represents a particular information structure, which we represent using the variable θ. The physical process simulations contained in the ESP generate a probabilistic estimate of the volume of water within a subbasin and contains: the interaction between soil moisture and rainfall runoff, snow accumulation and melt; response of a watershed in terms of runoff volume and timing of an input of rainfall; in-channel flow analysis, floodplain determination, and routing; and reservoir impacts (Restrepo 2017). We call this information structure $\theta = 0$ and consider it the reference case in our analysis. The information structure $\theta = 0$ yields a flood stage forecast $FS_0(s; t)$.

There are a variety of test metrics available to verify the forecast probabilities from the ESP. These metrics are used to evaluate specific attributes of forecast quality, such as reliability and discrimination (Brown et al. 2010). The conceptual models are analyzed and adjusted on a daily basis with the goal of accurately simulating streamflow while maintaining reasonable model water-basin states of nature. An adjustment, aka a "mod," can be made to the models when necessary and justified under an alternative information structure, say, $\theta = 1$. Forecast adjustments include precipitation type (rain or snow), amount and areal extent of snow cover, melt rate, amount of water in any conceptual storage, amount of rain, and amount of runoff that go into the conceptual models. The NCRFC sends the forecast data to the local Weather Office for production and released to the public. We use $FS_1(s; t)$ to represent this forecast.

Based on the premise that an independent data source can increase the statistical confidence of a forecast, an information structure could be made more informative with the addition of a confirmatory signal from an external observing source such as GRACE-DA. In this counterfactual case, we employ GRACE–DA as an independent data source that can allow for a second contemporary adjustment to the ESP. We label this information structure as $\theta = 2$ and the associated forecast as $FS_2(s; t)$.

The benefit of making model adjustments based on external observing systems is that they can help guide the forecaster. Here we build a consolidated hazard communication $FS_{12}(s;t)$ to produce a forecast that uses $FS_1(s;t)$ and $FS_2(s;t)$ that yields a forecast with greater informativeness.

3.2 Uncertain river discharge forecasts and public information dissemination

Flood hazard warning systems link scientific and loss data for a warning-outcome combination. A hazard warning communication employs an estimate of the exceedance probability (EP), in this case, a probability that river discharge will exceed a flood stage level, to inform stakeholders when to take actions to avoid damage (Economou et al. 2016). Relevant and accurate data are usable and more valuable in a river discharge forecast if they are timely. However, more accurate information may take longer to produce.

In our modeling framework, we assume that a flood hazard evolves with the passage of time as does the forecast to predict the onset of a major flood. In the first period following initiation of the process, the decision involves whether to issue a warning based upon $FS_\theta(s;1)$, the message available at time $t = 1$. For each successive time period of the forecast, a message includes a new component and all past signals and is potentially revised until the end of the planning horizon $t = T$, when a flood has occurred or the flooding season has ended. The conditional probability that represents an adjusted operational forecast is $FS_\theta(s;t)|FS_0(s;t)$, where $\theta = 1, = 2$, or $= 12$. These conditional probabilities inform the selection of mitigation actions, and because the conditional probabilities can vary across information sets, different information sets can lead to different mitigation actions.

The expected payoff of a timely decision is a sequential decision problem of level exceedance probabilities over a prespecified time horizon. In each time period prior to a major flood, a mitigation decision is made whether to invest in flood loss avoidance. However, the probability of a major flood hazard changes over time, and while a delay to take action implies the continuation of the existing action, it could be a suboptimal choice. The societal loss from not being able to make informed decisions is the cost of implementation delay. To represent this decision, given the messages received, the decisionmaker chooses to implement a pre-flood mitigation measure if the forecasted flood stage level $FS_\theta(s;t)$ is greater than or equal to the probability of exceeding a predefined river discharge rate $\overline{EP}$:

$$d_{i,t} = \begin{cases} 1 \text{ if } FS_\theta(s;t)|FS_0(s;t) \geq \overline{EP} \\ 0 \text{ if } FS_\theta(s;t)|FS_0(s;t) < \overline{EP} \end{cases} \quad (1)$$

where d_{it} is a binary variable that equals 1 if the decisionmaker chooses to implement a pre flood mitigation measure and equals 0 if the decisionmaker decides to delay an action. $\overline{EP}$ is the maximum exceedance probability that can be tolerated by the stakeholders. Estimation of $\overline{EP}$ is an integral component of pre flood hazard communication, management decision and associated costs. Decisions to communicate and take action by the USACE involve $\overline{EP}$s of 50% and 30% for a specific flood stage threshold (Schueneman 2011).

The total cost of mitigation, given actions taken by the decisionmaker $d_{i,t}$, is a standard sum of fixed and variable costs of mitigation ~~given by~~:

$$\sum_{t=1}^{T}[\bar{c}_{is} + (T - t)c_{is}] \cdot d_{i,t} \tag{2}$$

where $\bar{c}_{is}$ is the expected mitigation cost of a pre flood mitigation measure in location i for flood stage s and c_{is} is the additional cost associated with delaying a decision to mitigate by one time period. The per-period delay cost c_{is} is multiplied by the number of time periods before the flood event that the mitigation action is taken, $T - t$, in order to obtain the total cost of delay.

To identify the least cost decision for $d_{i,t}$, alternative information structures can be compared using their relative uncertainties (Lawrence 1999). In the statistical decision we can evaluate whether consolidating two independent observations in FS_{12} is more informative in a flood hazard message when used together as complimentary information. In essence, we can pool the observations from both sets of post processing data, which increases the precision of the forecast. Thus, the decisionmaker's actions can be reframed as based on whether independent observations are members of the same set among information structures θ, for flood forecasts FS_{θ}.

$$d_{i,t} = \begin{cases} 1 & \text{if } FS_1(s;t) \in FS_{12} \\ 0 & \text{if } FS_1(s;t) \notin FS_{12} \end{cases} \tag{3}$$

One way to determine if the consolidated message FS_{12} is from the same probability distribution as the adjusted current operational forecast FS_1 is using a Mann – Whitney U test (van Doorn et al. 2021, Ermakova et al. 2018). This test statistic ranks the data of the FS_{θ} distributions to be compared by providing a measure of their statistical similarity (Conover 1980). If the Mann-Whitney U test null hypothesis, $\text{H}_0\colon FS_{12} = FS_1$ is accepted, then there is no difference between the two distributions. On the other hand, if the alternative hypothesis, $\text{H}_0\colon FS_{12} \neq FS_1$, is accepted, there is a difference in the distributions (Whitney 1997). Accepting the null hypothesis suggests there is an increase in the precision of the operational forecast by adding independent observations to the existing forecaster adjustment (Lee 1989). The combined observations in FS_{12} increase the statistical confidence in the forecast (Devore and Peck 1997). With more input to the empirical component, FS_{12} would provide a positive economic value for a reduced implementation delay.

A second outcome of accepting H_0 is that the current operational forecast is verified, and justifies an earlier action to mitigate a potential disaster. If the adjusted forecasts do not meet the condition in the null hypothesis and the forecasts are significantly different, further adjustment could be needed and the decision will be delayed until the next forecast.

3.3 Value of Information (VOI)

We rely on the Value of Information (VOI) framework to estimate the economic value of the flood hazard forecasts. The framework compares outcomes in two different states of the world: a "reference case" in which decisionmakers take action based on FS_1 and a "counterfactual case" in which they take action using FS_{12}. The difference in the societal value of the economic outcomes between these two information cases yields the VOI of FS_{12}. While alternatives to the VOI framework, such as qualitative preference elicitation, exist for characterizing the societal value of forecasts, we choose to rely on VOI in this application because the theory of information structures as relating to forecasts, the optimization problem that leads to the selection of mitigation decisions, and quantitative measures of mitigation cost all can be linked within one quantitative model.

In the analysis of short term pre flood protection, economic value of forecast information is defined as the value of avoided losses, expressed in dollars, associated with timely implementation of mitigation. However, if there is uncertainty in a forecast, there is a deviation from the expected value for losses, which increases with distance from the mean. This deviation from the expected value can result in a delayed or inaccurate forecast that can create considerable uncertainty and increased decision risk. If the decision risk can be reduced, there is a savings that accrues to the hazard communication. We evaluate whether the consolidated message, the counterfactual, would provide that payoff as a reduction in the protection costs of a timelier hazard warning.

To formalize this payoff, let d_{it}^{0} represent the mitigation actions taken by the decisionmaker using forecast probabilities from the ESP and let d_{it}^{θ} represent the mitigation actions taken using the adjusted forecast probabilities.

The VOI of a forecast is the difference between the costs of mitigation, as defined in Equation 2, resulting from actions defined in d_{it}^{θ} *and* d_{it}^{0}:

$$VOI_{\theta} = \sum_{t=1}^{T}[\bar{c}_{is} + (T - t)c_{is}] \cdot d_{it}^{0} - \sum_{t=1}^{T}[\bar{c}_{is} + (T - t)c_{is}] \cdot d_{it}^{\theta} \quad (4)$$

We apply this equation in the reforecast example to estimate the economic value of an improvement in the timeliness of delivering the message with no loss of accuracy.

4 The 2011 flood in Valley City, ND

The 2011 flood in Valley City, ND was documented as a 100-year recurrence (KLJ 2016). The gage height data plotted in Table 1 show how the flooding evolved in the vicinity of Valley City below Baldhill Dam, which controls water coming down the river from Lake Ashtabula (USGS stream gage 05058000, BLDN8)) and near downtown Valley City (USGS stream gage 05058500, VCRN8)[3].

Table 1. USGS gage 05058500 height* [ft] from 2/15/2011 to 6/15/2011

Date and Time	Gage Height [ft]
02/15/2011 12:00 CST	5.50
02/22/2011 12:00 CST	4.87
03/01/2011 12:00 CST	4.81
03/07/2011 12:00 CST	4.56
03/15/2011 12:00 CST	4.29
03/22/2011 12:00 CST	6.25
03/29/2011 08:15 CDT (MIN)	3.33
04/01/2011 12:00 CDT	4.68
04/07/2011 12:00 CDT	10.95
04/15/2011 12:00 CDT	20.27
04/18/2011 20:30 CDT (MAX)	20.66
04/22/2011 12:00 CDT	19.34
05/01/2011 12:00 CDT	16.75
05/07/2011 12:00 CDT	14.50
05/15/2011 12:00 CDT	11.53
05/22/2011 12:00 CDT	8.96

[3] https://waterdata.usgs.gov/nwis/uv?site_no=05058500.

06/01/2011 12:00 CDT	7.11
06/07/2011 12:00 CDT	8.11
06/15/2011 12:00 CDT	6.85

Source: https://nwis.waterdata.usgs.gov/nwis/uv?format=html&period=&begin_date=2011-01-31&end_date=2011-06-18&cb_00065=on&site_no=05058500.

*Gage height (also known as stage) is the height of the water in the stream above a reference point. Gage height refers to the elevation of the water surface in the specific pool at the streamgaging station, not along the entire stream. Gage height also does not refer to the depth of the stream (https://help.waterdata.usgs.gov/tutorials/surface-water-data/how-do-i-interpret-gage-height-and-streamflow-values) except for the unique case where gage zero is exactly at the bottom of the stream.

The city's total emergency measures for a 100-year flood event require an estimated 380,000 sandbags and 180,000 cubic yards (CY) of clay. On April 15, 2011 the Detroit Lakes Tribune (DLT) reported that Valley City needed to add a foot and a half to the already installed levees to protect the area against what is expected to be a record crest of 21.2 to 21.5 feet on the Sheyenne River by Tuesday (April 19, 2011) (DL–Online 2011). The rush to install higher levees occurred following the news that more water had to be released from Baldhill Dam. It was the second surprise surge in a week for people living beneath the dam.

In response, Valley City and Barnes County purchased 400,000 sandbags with the goal of raising levees to 24 feet (reported by City Administrator Jon Cameron, 04/15/2011). An additional 80 National Guardsmen were requested to join the 106 already on duty. The USACE planned to increase Baldhill Dam outflows on April 15 from 6,500 cubic feet per second (CFS) up to 7,000 CFS. On April 17 or April 18, the USACE again intended to increase flows from Baldhill to 7,500 CFS, which would be a record discharge rate for the dam. The releases from Baldhill Dam were necessary to make room for additional inflows and to keep Lake Ashtabula from topping the dam in an uncontrolled release. The increased flow from the dam releases was expected to raise the river in Valley City to 21.2 to 21.5 feet.

The "2011 USACE Valley City Flood Field Report" provides a review of what occurred prior to and during the flood event (Schueneman 2011). Valley City decisionmakers intervene when the river stage reaches 17 to 17.5 feet. They developed a three-phase flood mitigation plan using clay levees, sandbags, and Hesco barriers, and given an assessment of initial hydrographs, aimed to implement protective measures between April 13 and 15. However, as portrayed by the DLT, the flood crest forecasts were dynamic, often shifting after the completion of each mitigation response phase, prompting multiple revisions to the city's operations. The crest of the flood was at 20.66 ft and 7,270 CFS on April 18 at the aforementioned USGS stream gage in Valley City (see Table 1).

Tables 2 and 3 present salient statistics of the 2011 event, which was declared a federal disaster (FEMA 2011). Following the flood, a Valley City Commissioner presented the types of property values at risk and the associated protection and response costs (ND State Water Commission October meeting 2011). The flood was modeled as a 500-year recurrence with a height of approximately 21 feet. Table 2 illustrates the extensive impact on real estate if an emergency levee were to fail. Ultimately, the community incurred various costs that, for the most part, avoided substantial damage to its real estate. Table 3 shows that primary impacts were mainly limited to roads and bridges.

Table 2. Valley City, ND values at risk in Spring 2011.

	Floodway	100 Year Floodplain	500 Year Floodplain	Total
Residential	$11,065,800	$38,111,200	$17,932,000	$67,109,900
Commercial	$8,932,100	$14,419,800	$16,878,500	$40,230,400
Exempt (est.)	$30,249,586	$54,995,997	$24,682,435	$109,928,018
Total	$50,247,486	$107,526,997	$59,493,835	$217,268,318

Source: Testimony of M. Pedersen, Valley City Commissioner, Water Topics Committee, October 10, 2011.

Table 3. Valley City, ND flood costs, estimated protection cost savings from an improved hazard communication with a reforecast of the river discharge and flood stage level in Spring 2011.

FEMA 2011	Cost	Damage
Total public assistance cost estimate	$43,547,540	
ND State Water Commission 2011		
Cost to protect Valley City	Total: $8,800,000	

	Emergency Dike Construction and Flood Preparation: $5,170,000 Removal of Dikes, Sandbags and Debris: $1,800,000 Repairs to Streets and Sanitary Sewer: $1,750,000 Buildings and Utilities: $80,000	
Federal and state share	$7,661,000	
City of Valley City	$1,043,000	
Road damage		$640,000
Storm Sewer station		$74,000

Sources: Costs and damages: FEMA Disaster Declaration (FEMA 2011) and ND State Water Commission October meeting (2011).

On the other hand, preparation and public assistance costs for mitigation and response were significant as estimated by FEMA, North Dakota government, and Valley City authorities. A summary of the actions undertaken by Valley City agencies and the costs of each phase are listed in Table 4. Phase 1 of the mitigation plan involved stockpiling clay for bridge closures and raising the embankments of lower elevation reaches up to 22.5 feet, which required 58,000 CY of clay for emergency levees that were built between April 2 and 9. Phase 2 entailed increasing the protective measures if conditions warranted. If so, 1.5 feet would be added to existing levees using 65,000 CY of clay. The second mitigation action began on April 11 (flooding was occurring) and was completed on April 14, but the following day's forecast showed the river cresting at 21.5 feet, necessitating all levees to be raised to 24 feet and the construction of contingency levees behind all sandbag and Hesco lines. This undertaking required an additional 40,000-50,000 CY of clay for a total of 123,000 CY. Phase 3 was set as the response at an EP of 30% for a major flood event without waiting for a change in conditions and concluded on April 19.

Table 4. 2011 Emergency Levee Construction Cost

Emergency levees for risk management	Phase 1	Phase 2	Phase 3 planned (Counterfactual)	Phase 3 implemented (Reference)

Protection Effectiveness	Protect City to 50% event (19.1-feet)	Phase 1 and if conditions warrant raise to 30% event (20.4-feet)	Protect City to 30% event (20.4-feet)	Protect City to 24-feet and construct contingency levees behind all sandbag and Hesco lines
Effort	5-6 days, 12 hrs. per day	4-5 days, 24 hrs. per day	9-10 days, 24-hrs per day	City priorities: 1. Downtown business district 2. Valley City State University 3. Remaining areas
Total cost			$1.3M	$3.02M

Source: R. Schueneman, Field Report, Sheyenne River, Valley City in Barnes County, ND, May 2011

The effort required the coordination of several entities, including the National Guard and the city's police and fire departments. Officials met daily at the peak of the flood event, and generally every other day at both ends of the timeline. Flood impacts included the closure of five of the city's eight bridges, operational pressures on the sewer system with the onset of higher river flows, and the plugging of sluice gates on 80 of the levee system's culverts and drainage basins. While bridge closures restricted access across the city, an evacuation plan was available to residents. The provision of a "hot spot" list prepared by the USACE also enabled Valley City to prioritize historically vulnerable locations for protective measures.

5.0 Analysis

In our area of interest, the NCRFC issues flood forecasts when there is an indication of near-term higher river flow stages in communities along the Sheyenne River that could require action for flood protection. In addition, USACE Flood Control officials must decide whether to release water from Lake Ashtabula that can increase flow through Valley City and affect both the city and nearby croplands. As described earlier, as part of the forecast process, the performance of outputs from the ESP (also known as the Open Run) is compared to past observations in the historical climatological distribution, and based on the comparison, the forecaster may decide to perform some modifications. Once the forecaster judges that the comparison is acceptable, the forecast FS_1 is made official and is distributed to the corresponding weather forecast offices for publication online. Further adjustments can be made to the amount of precipitation forcing if the observations look questionable. One justification would be to add signals from GRACE–DA to produce another independent adjusted forecast, FS_2. In the present study, only the root zone soil moisture output from GRACE is incorporated into FS_2, as the SAC-SMA framework allows for a mapping between the root zone and the conceptual model storages (Koren et al. 2007). It does not directly model groundwater. The percent saturation as estimated from GRACE is determined from the soil layers and then converted to a level of "fullness" of the conceptual SAC-SMA storages. With these soil moisture states updated, the conditional simulations are rerun to produce the GRACE-DA exceedance probabilities.

A non-operational copy or "standalone" instance of CHPS is used to produce the retrospective example below in which we show that the GRACE-DA adjustment can enable an earlier decision for mitigation. The resulting consolidated message FS_{12} would reduce decision maker uncertainty through an increase in the statistical confidence of a forecast (Sinn 1983). Thus, pooling observations in FS_{12} can be considered an accurate, and potentially earlier hazard communication with relatively greater informativeness. Consistent with our conceptual framework above, we estimate $\bar{c}_{is}$ and $(T-t)c_{is}$, where the second metric represents the additional mitigation cost caused by delay in a decision in Spring 2011.

During the early spring of 2011, the probabilistic seasonal river discharge forecast signaled a low river flow. In our analysis, we use estimates that reflect Baldhill Dam releases and VCRN8 to represent potential impacts to the Valley City community. The March 11 ESP simulation for the period between March 18 and June 17 is shown as the graphed black line in Figure 2a. Inspection shows the threshold for taking action is below the minor flood stage, when the river flow is at an expected 3,125 CFS. For the ESP forecast, the lowest flood stage of 15 ft (3,720 CFS) has an $EP = 20\%$ at the Valley City gage as shown in orange, and an $EP = 10\%$ for a major flood stage 17 ft (4,760 CFS) shown in purple.

Figure 2b illustrates the historical climatology distribution, represented by the blue line with circles, the NCRFC adjusted forecast (FS_1), represented by the black line with circles, and the GRACE-DA adjusted forecast (FS_2), represented by the black line with triangles. The March 2 FS_1 forecasts a major flood with potential disastrous consequences (see Table 5). The forecast for the period March 7 – June 5 as shown in Table 5 has an $EP = 50\%$

for a flood height of 17.2 ft (in excess of 4,760 CFS) and an $EP = 30\%$ for a flood height of 18.6 ft. Expected flood height increased to 17.2 feet, which could trigger a response for a Phase 1 response of the Valley City flood management plan that was completed. Phase 2 also was completed, but the updated forecast necessitated higher protective barriers and more labor cost. As conditions changed rapidly, the updated operational forecast produced exceedance probabilities for flood height enumerated in Table 5 and shown in Figure 2b.

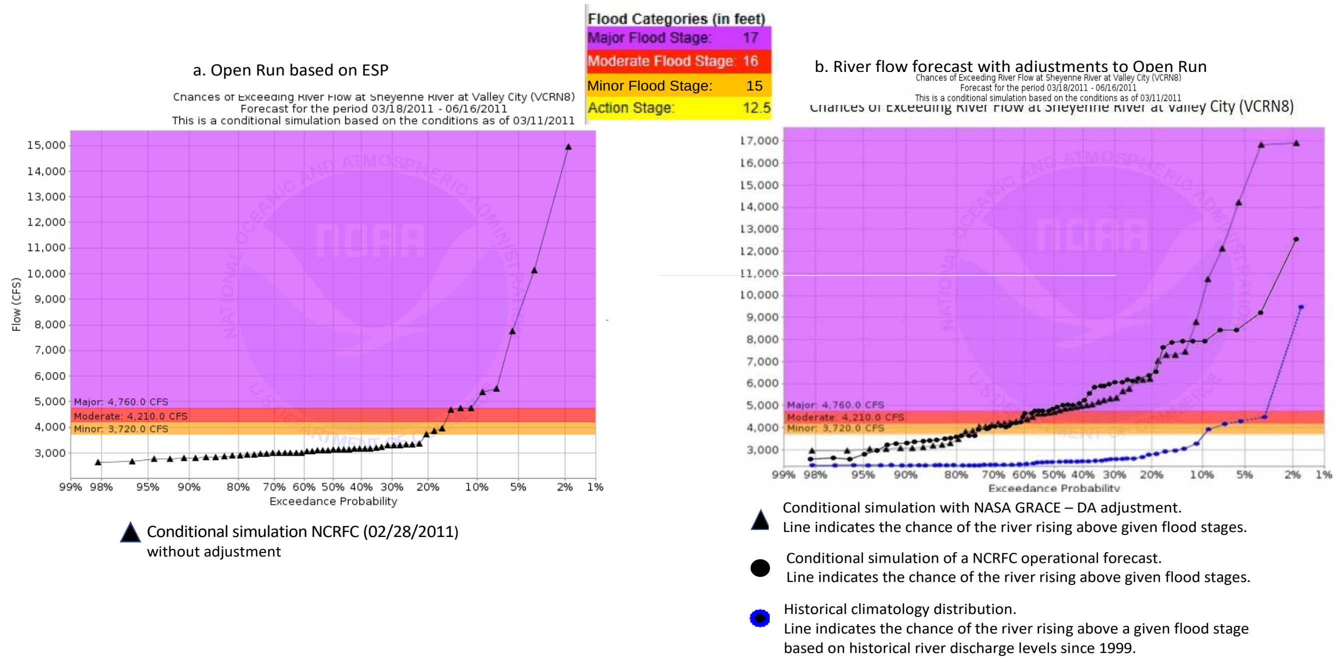

Figure 2. Exceedance probabilities and flood stage for historical, current operational NCRFC, and GRACE-DA adjusted forecasts for the period of 3/18/2011 – 6/18/2011 (images courtesy of NCRFC)

A decision was made by the community to consider undertaking Phase 3 to protect the city. However, there was uncertainty because the forecasts changed frequently, which affected the city’s operations and dam release expectations.

Table 5. Estimated flood height at VCRN8 for 3/7/2011 – 6/5/2011

$EP(FS_{03022011})$	90%	80%	70%	60%	50%	40%	30%	20%	10%
Flood height in feet	12.8	14.0	14.8	15.9	17.2	17.5	18.6	19.0	20.9

Source: NWS North Central River Forecast Center, 1026 AM CST, MAR 02 2011

FS_2 includes a 3-month forecast of root zone soil moisture wetness from GRACE-DA shown in Figure 3. The map shows the approximate area of the Sheyenne River basin outlined by the red circled area and the location of Valley City just inside the circle. The map also illustrates that basin wetness is considerably above average during the forecast period and that Valley City could experience high river flows. The impact of the GRACE-DA adjustment can be seen in Table 6 and is represented in Figure 2b by the black line with triangles. The ESP shows an $EP = 50\%$ for a 3,100 cfs river flow until April, which is below any flood stage level. Of particular interest is the GRACE-DA adjusted forecast for March 18 – June 17. This is the period when FS_1 forecasts are greater than 4,750 cfs on March 2 in Table 5 and for FS_2 on March 1 in Table 6, confirming the operational forecast. Thus, for this critical period, the GRACE-DA and NCRFC forecasts were messaging that a major flood risk should be of concern to decision makers as early as March 2.

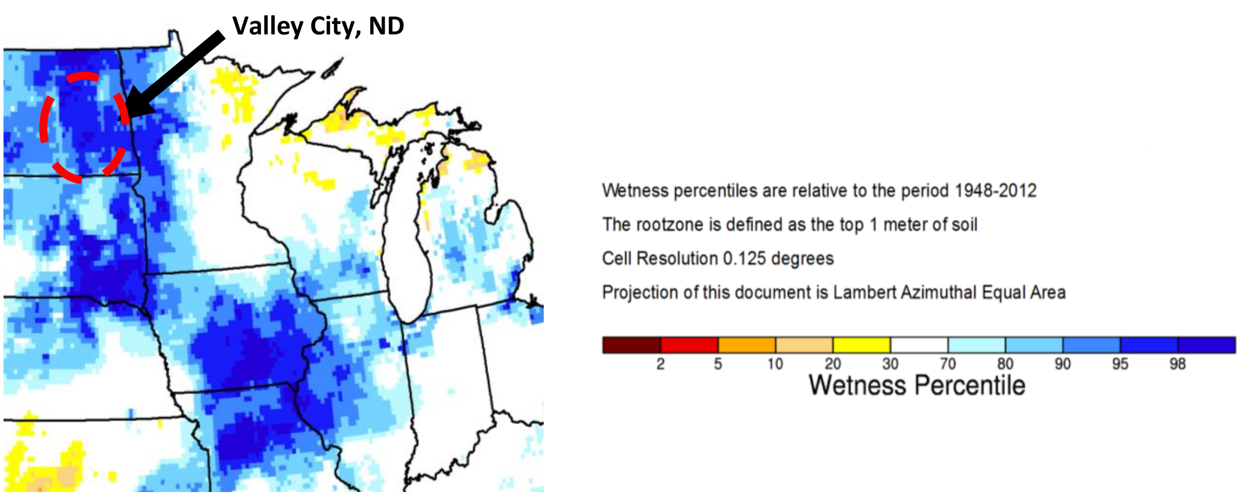

Figure 3. GRACE – based root zone soil moisture drought indicator 2/28/2011 (https://nasagrace.unl.edu)

Table 6. Sheyenne River discharge and flood risk forecasts for January – July 2011 with an Open run (ESP) and a GRACE-DA adjustment for the Valley City, ND at USGS river gage 05058500

VCRN8 QINER	10% [cfs]	20% [cfs]	50% [cfs]	Flood risk (%)	Major flood risk (%)
Open (ESP) 01/18/2011 – 04/17/2011	4,841.5264	3,514.3191	3,022.6165	< 20%	10%
GRACE adjust 01/01	4,475.1245	3,500.7190	2,994.4163	< 20%	< 10%

01/18/2011 – 04/17/2011					
Open (ESP) 02/18/2011 – 05/17/2011	5,317.7290	4,590.9248	3,126.7170	< 10%	15%
GRACE adjust 02/01 02/18/2011 – 05/17/2011	6,598.2358	5,016.8271	3,081.0168	< 10%	20%
Open (ESP) 03/18/2011 – 06/17/2011	5,372.3296	3,723.9202	3,125.0171	< 10%	15%
GRACE adjust 03/01 03/18/2011 – 06/17/2011	10,733.8594	6,198.2339	4,722.4253	75%	50%
Open (ESP) 04/18/2011 – 07/17/2011	10,559.5576	8,192.2441	5,075.5273	> 98%	75%
GRACE adjust 04/01 04/18/2011 – 07/17/2011	12,752.9688	11,063.7607	8,726.9473	> 98%	> 98%

Source: Michael DeWeese, Development and Operations Hydrologist National Weather Service North Central River Forecast Center 2019

For the consolidated message $FS_{12}(s;t)$ to be useful, we test whether the conditional probabilities from the two forecasts come from the same underlying population and can be used together. We do this with a Mann – Whitney U test in which the null hypothesis H_0 is that $p\left(FS_1(s;03022011)\right) = p\left(FS_2(s;03012011)\right)$. We applied the test for the two black exceedance probability curves in Figure 2b. In a two-tailed test, if the test statistic U_{obs} is less than or equal to the critical value U_{crit}, H_0 is rejected in favor of H_1 which is the alternative hypothesis that the two populations are not equal. We find that U_{obs} = 14.5 for the NCRFC curve (n = 8) and U_{obs} = 21.5 for the GRACE-DA curve(n = 6). U_{crit} values for the test are 8 for a 0.05 level of significance and 4 for a 0.01 level of significance. Because $U_{obs} > U_{crit}$ for both levels of significance, we cannot reject H_0. We thus cannot reject that the exceedance probabilities and river flows with NCRFC and GRACE-DA in $FLS_{12}(s;t)$ forecasted flood stages are derived from the same statistical population. This outcome of the test suggests that the GRACE-DA forecast could assist the NWS and the USACE in making hazard communications more temporally reliable.

Concurrence of the two adjusted forecasts signaled a greater mitigation effort could have been implemented earlier with no loss of accuracy. On March 2, the consolidated forecast met the requirement of $d_{i,t} = 1$. A second independent adjustment could have changed the action date to $t - 5$ rather than at $t + 1$, which was the April 18 – July 1 forecast, executed just as the flood was occurring on April 11. In Valley City, the consolidated forecast would have communicated greater urgency for Mitigation Phase 3 implementation earlier, which could have reduced the cost of protection. $FS_{12}(s;t)$ provides an incremental economic value that stems from the addition of the GRACE-DA adjustment input to the mitigation timeliness (Qian et al 2009, Gossner 2000). By using the consolidated forecast, Valley City could have chosen to employ Mitigation Phase 3 by March 18, 2011.

An implementation delay caused a scramble for resources resulting in a higher price of clay equivalent to \$6.11 per CY placed (Schueneman 2011). The difference in protection cost between the reference $FS_0(s;t)$ and consolidated $FS_{12}(s;t)$ forecasts is the VOI of GRACE-DA. Had the decision been to implement Phase 3 five days earlier as a result of the consolidated forecast, a monetary savings of \$1.7 million could have been realized. This monetary estimate is a quantitative measure of the economic value of GRACE-DA as a value in use.

Because this is an ex-post assessment, our VOI estimate is based on realized forecast delays and mitigation costs and is thus not subject to uncertainty. However, as a simple sensitivity analysis, we can discuss the impact of alternative avoided forecast delay times on VOI by assuming that mitigation costs increase linearly with delay time. Under this assumption, cutting the five-day avoided delay time attributable to GRACE-DA by half would reduce the VOI to \$0.85 million, while doubling the avoided delay time would increase the VOI to \$3.4 million. Note that the assumption that mitigation costs increase linearly with delay time is likely to lead to an underestimate of VOI when more delay is avoided.

6.0 Discussion

The spring of 2011 brought the second 100-year flood to the Sheyenne River Basin in 2 years. Following the flood, the city of Valley City proposed a multistep approach for permanent protection of the community. Valley City partnered with the USACE to increase public safety, reduce the dependency on sandbags and Hesco barriers, lower risk of flood damage to neighborhoods, the downtown business district and Valley City State University, increase efficiency of emergency levee construction, and enable permanent flood protection (North Dakota State Water Commission 2011). The State of North Dakota has invested in permanent flood protection for the 100–year flood plain in Valley City over approximately a ten-year period. As of August, 2023, the Valley City program is on hold for the final buildout phase of the project until a Conditional Letter of Map Revision (CLOMR) is submitted to FEMA for the full build out of the permanent flood protection system. The CLOMR will identify any changes to the base flood elevation because of the completed flood protection system and any mitigation required because of impacts to structures (https://www.newsdakota.com/2023/08/22/valley-city-preparing-4th-phase-of-permanent-flood-protection/).

Permanent flood protection for the community is not a certainty, especially as the regional climate changes during the upcoming decades. North Dakota is part of a large area in the northern and central US with projected increases in winter precipitation for the middle of the 21st century (Frankson et al. 2017). Spring precipitation also is projected to increase. The effects of potential flooding in the Valley City 2045 comprehensive plan identifies the areal extents of the impacts for 100 and 500–year floods (Stantec 2019). The report illustrates the dynamic nature of the flood hazard of increasing flood size, greater severity, and higher frequency.

As shown in Table 2, the expected damage of the 500-year flood is an additional $59.2M for Valley City. Most significantly, the greatest impact of a major flood would be on the city's commercial sector. This forecast for damage would exceed the current plan design and require additional protection above the 100-year flood hazard. Major floods will need to be forecast with increased confidence so that the community can be better prepared. A consolidated forecast with a GRACE-DA adjustment offers a novel form of verification of an operational forecast. In our case study, the $FS_{12}(s;t)$ consolidated forecast would produce a hazard communication that is timelier with no loss in accuracy at less cost (NRC 2003). While the intent is to reduce temporal uncertainty in community mitigation decisions, the innovation of incorporating GRACE-DA requires both capital and labor to accomplish new tasks by the forecaster (Acemoglu and Restrepo 2019). These new tasks can increase the productivity of the forecast via a reduction in decision risk but also requires review and testing.

7.0 Conclusion

We have estimated the VOI of improved timeliness and reliability of a probabilistic operational river discharge forecast with forecaster and GRACE-DA adjustments. The VOI is driven by reductions in the impact of delayed actions from decisions using seasonal flood forecasting and empirical updates. By pooling the observations from both sets of post processing data, an increase in the precision of the forecast is possible. In the example, a 5-day reduction in the timing for executing loss avoidance actions based on a consolidated NCRFC + GRACE-DA forecast for a flood crest greater than expected would have led to savings in mitigation costs. The consolidated forecast can provide more confidence in communications with the USACE and other stakeholders to lower pre-flood mitigation costs to a community. In making this statement, we note that this was a single case study for which GRACE-DA performed well. Prior to operationalizing such a system, one would perform site-specific evaluation and calibration of the forecast system. The latency of GRACE-DA products, which was not an issue in this retrospective analysis, would also need to be minimized. We also did not compare GRACE-DA to other satellite-informed forecast products that might play a similar role; design of an operational system should include a survey of available model and data assimilation options.

It is becoming clear from climate projections that permanent protection for the current stage levels for the 100-year event may not be enough. Accurate, timely seasonal forecasts will be of increasing value as the potential severity of major floods increases with time and as groundwater levels rise. Increases in forecast confidence also are important for timely decisions in longer-term planning. Even though a community such as Valley City, ND should continue to prepare to control and avoid flood disasters by investing in permanent structures, emerging trends of warming and increased precipitation mean that protection in a major flood also will require timely, informative flood forecasts.

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