Received: 18 January 2019 | Revised: 25 July 2019 | Accepted: 18 September 2019

DOI: 10.1111/jfr3.12573

ORIGINAL ARTICLE

CIWEM Chartered Institution of Water and Environmental Management Journal of Flood Risk Management WILEY

Benefits of an advanced quantitative precipitation information system

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Funding information
National Oceanic and Atmospheric Administration

Abstract

A reconnaissance-level regional resource accounting approach was applied to quantify benefits associated with an advanced quantitative precipitation information (AQPI) system being developed for the San Francisco Bay area. The AQPI system would provide incrementally higher resolution monitoring of rainfall events and longer lead-time forecasts compared to current practice. AQPI system costs were estimated to have initial costs of \$66 M and \$3.3 M annual operation and maintenance; these translate to a present value cost (at 10 years and 6%) of \$90 M. Benefits were associated with avoided flood damages, increasing water supplies, and enhancement of ecological, recreational, and transportation services. Total incremental benefits are estimated to be \$61 M/year. Taken by category about 48% of the benefits are for flood damage mitigation (\$29 M/year), with water supply (32%, \$19.5 M/year), ecosystem (3.3%, \$2 M/year), recreation (7.6%, \$4.6 M/year), and transportation (9.5%, \$5.8 M/year). These translate to a present value benefit of \$449 M which computes to a base-level B/C ratio of 5 to 1. Sensitivity analysis indicates a range of B/C up to 10 and down to 2. Given that most of the benefits are dependent on appropriate actions by hazards and water management agencies and citizens, then the AQPI project development involves outreach and training to maximize responses.

KEYWORDS

benefit–cost analysis, damage mitigation, flood forecasting, water supply

1 | INTRODUCTION

Advanced hydro-meteorological (i.e., hydromet) observations and forecasts can be critical to water resources management efforts in any location. The hydromet monitoring and forecasting programs of the National Weather Service (NWS) and the National Oceanic and Atmospheric Administration (NOAA) Hydrometeorology Testbed (HMT; https://hmt.noaa.gov/) involve deployment of advanced sensor networks, assimilation of the data collected, application of mathematical models of the atmosphere and watersheds, articulation of decision-relevant information, and dissemination of this information to users. A project involving these elements, called the Advanced Quantitative Precipitation Information (AQPI) system, is being designed and deployed in the San Francisco Bay (SF Bay) area of California to enhance NWS forecast operations.

This paper addresses the economic feasibility of the AQPI system to provide a benefit–cost basis that would qualify for investment. Improvements in severe weather detection, tracking, and forecasting can result in benefits for public safety and water resource management. Beneficial responses depend on a spectrum of weather and climate forecast time frames ranging from real-time (nowcasting) updates on weather and river flow conditions, to short- and near-term seasonal forecasts. Depending on the resource management purpose, there are various actions which might be taken to mitigate adverse impacts of severe weather, or to maximize performance of available water.

The SF Bay region includes all or portions of the nine counties, including Alameda, Contra Costa, San Francisco, San Mateo, Santa Clara, Marin, Napa, Solano, and Sonoma counties. With a population of 7.8 million (in 2017), the SF Bay metropolitan region is the second largest in California and the fifth largest in the nation. According to a recent California Department of Water Resources (CaDWR, 2013a, 2013b) report, many parts of California, including the SF Bay Area, are at risk of catastrophic flooding (e.g., Porter et al., 2012). In addition to public safety, infrastructure dedicated to water supply, ecosystem services, and transportation can be impacted.

2 | ADVANCED QUANTITATIVE PRECIPITATION INFORMATION SYSTEM

The AQPI system is a regional-scale approach directed to improving the temporal and spatial resolution of severe weather detection, tracking, and forecasting for the SF Bay area. Rain storms are highly variable in time and space and are not sufficiently resolvable using current rain gauge and NWS NEXRAD weather radar information.

The project involves development and deployment of advanced radar weather sensors, data assimilation, numerical weather prediction (NWP) and hydrological models, and system integration to support weather and flood forecasting and warnings dissemination. On the west coast U.S., there is emphasis on the "atmospheric river (AR)" phenomenon which are threads of concentrated near-surface water vapor over the Pacific Ocean that play an important role in the storms and floods (e.g., Ralph, Coleman, Neiman, Zamora, & Dettinger, 2012). NWS NEXRAD radar coverage tends to overshoot low-level ARs and is blocked by terrain in some sectors.

The AQPI system uses the AR satellite detection and tracking tool (https://esrl.noaa.gov/psd/psd2/coastal/satres/

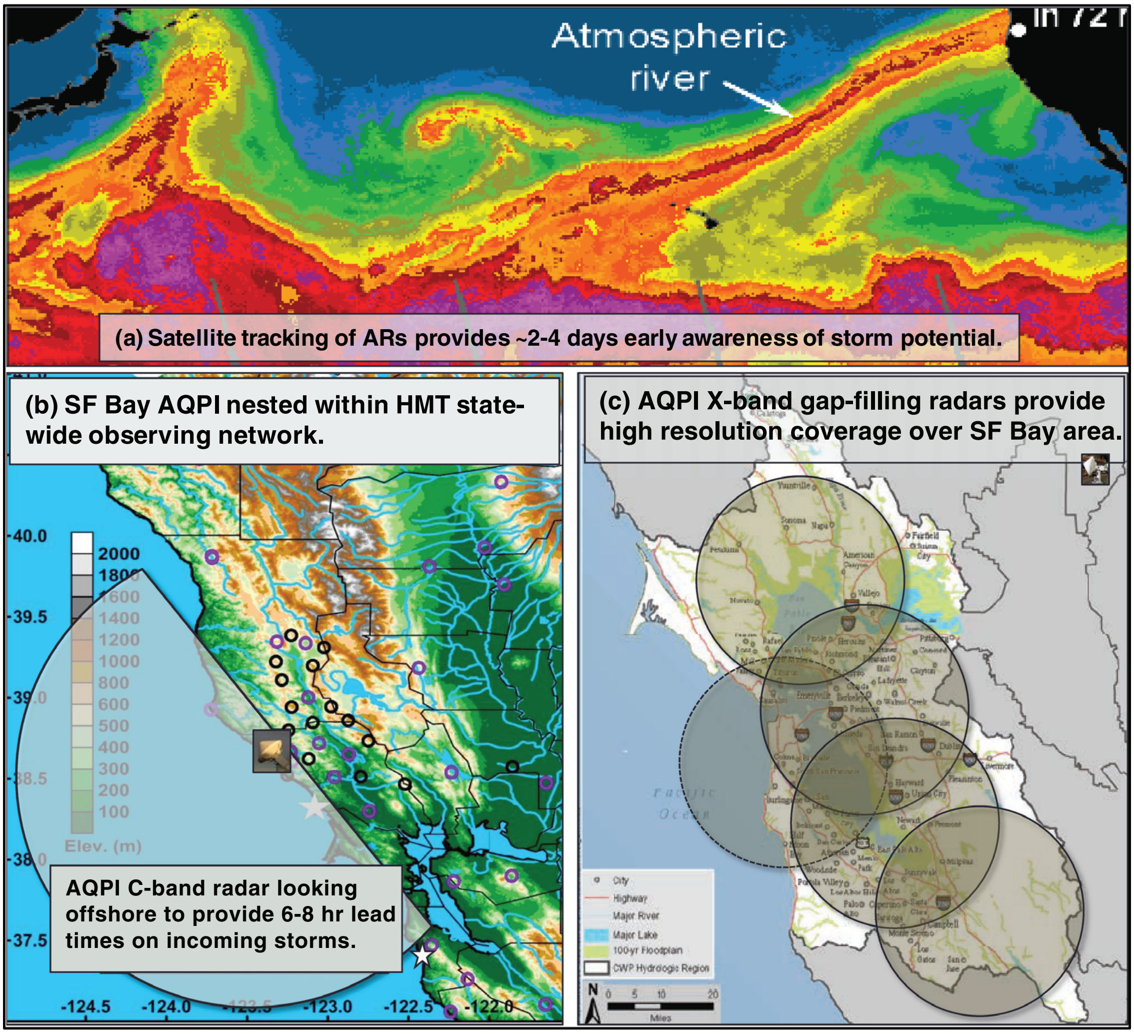

FIGURE 1 AQPI system involves (a) satellite detection and tracking of atmospheric river events over the Pacific Ocean (2 to 3 days lead time), (b) coastal C-band (6 to 8 hr lead), and (c) gap-filling X-band radars (2-hr lead time)

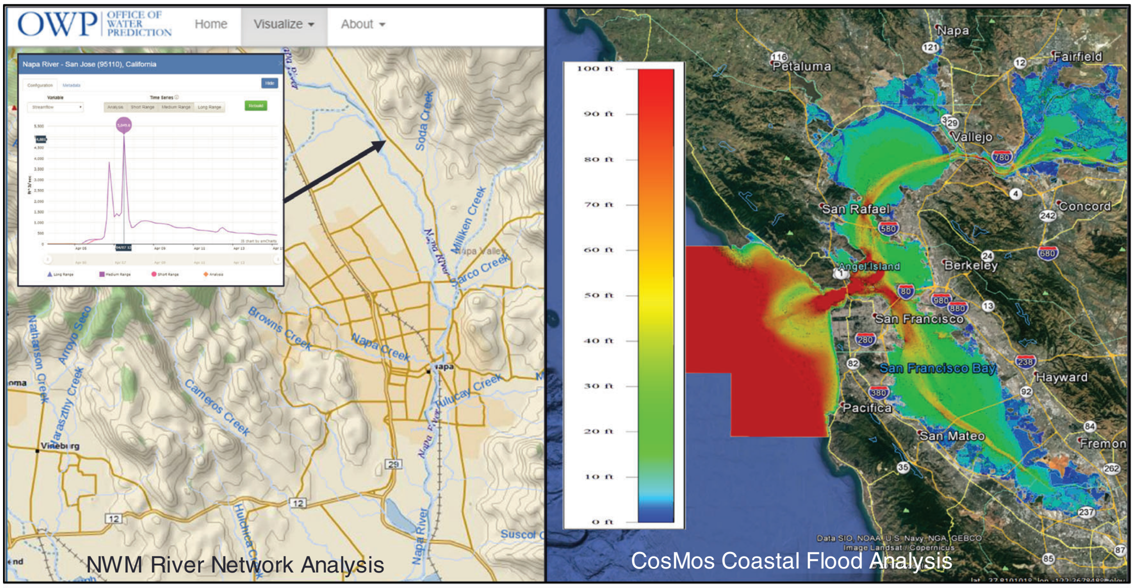

FIGURE 2 (a) Distributed hydrologic model, the NWS National Water Model (https://water.noaa.gov/), provides flash flood guidance for all drainages in the region. (b) CoSMoS coastal storm model (Barnard et al., 2014) forecasts flood inundation areas along shore and up tributaries

data/html/hmt_sat.html) to gain awareness that storms are generating over the Pacific Ocean (1-day lead time). NOAA's new Geostationary Operational Environmental Satellite-S (GOES-S) satellite is expected to provide 2 to 3 days lead time on potentially large storms (Figure 1a). A Doppler C-band weather radar located on the coast will point over the Pacific Ocean (Figure 1b) to track incoming low-level storms (6 to 8 hr lead time) and four lower cost gap-filling X-band radars will provide up to 2-hr lead time with 2-min updates (Figure 1c), and will provide high resolution coverage over populated and flood prone urban areas.

In addition to storm detection and tracking, the satellite and radar data will be assimilated and inform a high resolution NWP model, the High Resolution Rapid Refresh (https://rapidrefresh.noaa.gov/hrrr/) which will improve forecast accuracy and resolution out to 18 hr. The recently released WRF-Hydro National Water Model (NWM, http://water.noaa.gov/map, Figure 2a) will provide high resolution distributed hydrologic model details on watershed runoff and flash flooding out to 18 hr at 1-km resolution with 1 hr updates. The NWM outputs will be coupled to the Coastal Storm Modeling System (CoSMoS, Barnard et al., 2014, Figure 2b) to simultaneously forecast flooding along the SF Bay margin due to tributary runoff, and tides, storm surge and waves.

Current hydrologic forecast practice involves the NWS California-Nevada River Forecast Center (CNRFC, https://www.cnrfc.noaa.gov/) which provides flow forecasts for about two dozen river and reservoir locations in the SF Bay area. The CNRFC also issues a daily gridded Flash Flood Guidance (FFG, Carpenter, Sperfslage, Georgakakos, Sweeney, & Fread, 1999) product defined as the average inches of rainfall for a given duration required to produce flash flooding in small streams. The NWS Weather Forecast Offices use the FFG and stream gauge data to provide flash flood watches and warnings for local streams. These forecasts are issued each morning with 12-hr updates as needed during significant runoff events. Overall, compared to current practice the AQPI system is expected to increase flash flood forecast lead times by 12 hr with higher spatial resolution and more frequent updates. The NWM provides forecasts for 11,000 stream reaches in the nine-county area with a 1-hr update interval.

Costs of an AQPI system occur in several categories for monitoring, analysis and assimilation, prediction modeling, and system integration. Total startup costs are \$33 M with an equal amount already invested or planned for a total \$66 M. Annual operations and maintenance costs are estimated to be \$3.3 M/year. Assuming a 10-year operations horizon the present value cost at 6% discount rate is \$90 M.

3 | AQPI FORECAST BENEFITS

The SF Bay area AQPI system hydrometeorology (hydromet) information products can be expected to provide benefits beyond current practice exceeding costs through (a) avoided flood damage costs, (b) maximization of reservoir capture, (c) enhancement of ecosystem services and water-based recreation, (d) minimization of water quality impacts from sewer systems, and (e) enhancement of public safety and convenience for the various transportation modes (roads, airports, trains, and ports).

Methods for benefits estimation applied here include avoided cost, market valuation, and transfer of benefit values estimated in other studies. An extensive literature review provided information on established methods for benefits estimation (CaDWR, 2008, 2009a, 2010; Carsell, Pingel, & Ford, 2004; King & Mazzota, 2003; Kite-Powell, 2005a; Kite-Powell, 2005b; Lazo & Chestnut, 2002; Nordhaus, 2008; Stallings, 1997; USACE, 1994, 1996; USWRC, 1983; Viscusi, 1993; Yoe, 1994).

This regional benefit accounting approach is considered reconnaissance-level as it relies on general indicators for the most part and does not involve detailed data collections and economic analyses that might be applied for a more in-depth study. Consequently, the regional accounting approach as applied is considered to yield partial and conservative estimates of benefits. In general, the confidence levels for benefits estimations presented are in the moderate to low range. A range of benefits is computed through sensitivity analysis by varying the base-level factors to reflect high-level (optimistic) and low-level (pessimistic) selections.

3.1 | Emergency response for flood damage mitigation

Benefits of flood warnings are keyed to lead time; the time between the issuance of the warning and the occurrence of the flood (NHWC, 2002). Saving lives and property with less than 18 hr lead time is generally limited to getting out of harm's way, and moving highly valued property, such as automobiles, equipment, and major appliances. When lead times are longer than 18 hr, floodplain residents can flood proof and flood fight (construct temporary levees, place sand bags, and so on). For the AQPI system increases in flood warning lead time are projected in the range of 12 hr.

Day (1966, 1970) developed and applied a technique, the so-called "Day curve" to predict annual benefits resulting from the use of NWS hydrologic forecasts. The original Day curve indicates a maximum loss reduction of 35% of total damage (e.g., structure and contents), and assumes a public response rate of 100%. At a 12-hr lead time, the Day Curve indicates a 22% damage reduction. The technique considers the probability of floods at a given depth and the dollar damage associated with the flooding depth. Comparable studies (Bock & Hendrick, 1966; Kates, 1965) indicated a 10 to 40% reduction in flood damage due to hydrologic forecasts. The National Hydrologic Warning Council (NHWC, 2002) recommends a 10% reduction.

The basic concept of the Day curve was extended by Carsell et al. (2004) who developed an approach involving computation of expected annual damages (EAD) using a depth-damage function for residential contents for a range of lead times. For significant flood events, about 50% of the $100,000 contents is susceptible to damages, and approximately 10% of that amount can be avoided with a 12-hr increase in lead time.

The Carsell et al. (2004) study also addressed concerns with the efficiency of the warning dissemination and respondent reactions. The following model was proposed to measure efficiency of flood warning:

$$\text{Efficiency} = F_{rw}\, x\, F_w\, x\, F_c \tag{1}$$

where F_{rw} = fraction of the public that receives a warning; F_w = fraction of the public that is willing to respond; and F_c = fraction of the public that knows how to respond effectively and can respond (or has someone to help them). A recent report for CaDWR (2010) suggested the damage reduction factors shown in Table 1. Higher levels of damage reduction are sought through preparedness outreach and response exercises, which is an integral part of the AQPI project.

For the AQPI project, a 10% incremental damage reduction on $50,000 susceptible contents, and a 75% response rate are used as the additional reduction to be expected beyond current capabilities.

For the SF Bay area, a report on California's Flood Future (CaDWR, 2013a, 2013b) tabulated the number of structures in the 100- and 500-year floodplains (Table 2). The nine-county region has 126,000 structures in the 100-year floodplain and 373,000 structures in the 500-year floodplain. Assuming an average $50,000 value of (susceptible) contents per structure (after Carsell et al., 2004), then the total potential contents damages are $6.3B and $18.7B respectively. With the 100- and 500-year data points a damage-frequency chart can be plotted to support full spectrum damage-frequency curve estimation for each county. The EAD is computed by taking the area under the damage-frequency curve (Figure 3); Table 2 tabulates the results. Using this approach, the total EAD for structure contents is estimated to be $194 M per year for the nine-county area. It is this amount that can be used to estimate reductions associated with timely flood warnings.

Assuming the 10% incremental damage reduction level with a 75% response rate, then the expected damages would be reduced by $29.1 M per year. Taking 10 years as the base service life of the AQPI equipment and related

TABLE 1 Percentages of actual vs potential damages (CaDWR, 2010)

Warning time	Experienced community	Inexperienced community
Less than 2 hr	80%	90%
2 to 12 hr	80–40%	80%
Greater than 12 hr	40%	70%

TABLE 2 Expected annual damages to structures contents in SF Bay area

County	Structures in 100-year floodplain	Structures in 500-year floodplain	100-year contents damages* ($M)	500-year contents damages* ($M)	Exp. annual contents damages ($M/year)	Damages avoided* ($M/year)	Present value (6%, 10-year) ($M)
Alameda	10,100	38,500	$505	$1,925	$18.0	$2.71	$19.9
Contra costa	15,300	25,300	$765	$1,265	$19.3	$2.89	$21.3
Marin	13,300	22,100	$665	$1,105	$16.8	$2.52	$18.6
Napa	4,900	6,500	$245	$325	$5.8	$0.88	$6.5
San Francisco	0	0	$0	$0	$0.0	$0.00	$0.0
San Mateo	30,300	44,700	$1,515	$2,235	$36.9	$5.54	$40.8
Santa Clara	37,100	201,600	$1,855	$10,080	$75.9	$11.38	$83.8
Solano	7,200	23,100	$360	$1,155	$11.8	$1.77	$13.0
Sonoma	7,900	11,600	$395	$580	$9.4	$1.41	$10.4
Total	126,100	373,400	$6,305	$18,670	$194.0	$29.1	$214.1

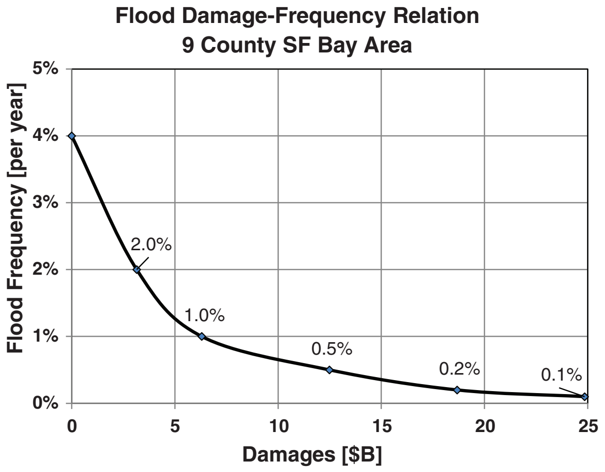

FIGURE 3 Flood damage frequency relation forms the basis for expected annual damage estimates

infrastructure, and discounting at 6% (recommended by the CaDWR, 2008), the incremental equivalent present value benefits of the AQPI system for structure contents damage reduction would be $214 M.

3.2 | Reservoir storage for flood control and water supply

Reservoir storage is used for capture of surface runoff and redistribution of the stored water over time for various uses such as water supply for municipalities, irrigated agriculture and fisheries flows. Multi-purpose reservoirs typically have several zones for flood control and conservation to meet water supply demands and other non-flood period purposes. Reservoir volume for flood control involves reserved or empty space by which to capture flood runoff. Flood-control projects may be regulated according to a prescribed operational schedule or "rule curve" which defines the seasonal storage levels for flood control on top of the conservation zone. Flood zone operations involve capture of high flows and allowing storage increases into the flood zone. Once the flood event passes the stored water is released in a controlled manner according to the rules.

An emerging concept is for forecast-based operations (FBO), or forecast informed reservoir operations (FIRO), in which decisions for flood control operations are based on forecasts of heavy precipitation events, or the lack thereof. FIRO involves a more adaptive approach than the fixed rule curve approach (e.g., Jasperse, 2017; Pugner, 2003). If a heavy precipitation event is forecast and imminent, then the reservoir storage level can be drawn down using a pre-release strategy. The reverse strategy is if there are no forecasts of heavy precipitation events, then the storage level may be allowed to remain in the flood zone. Then, the captured water could carry over into the non-flood season and be used to sustain water supply and other purposes. The FIRO approach also applies for water supply (discussed in the following).

Benefits of FIRO can be estimated using a "reoperations" simulation approach that accounts for the mass balance of reservoirs inflows, releases and changes in storage, and the alternate operations. A case study for Lake Mendocino, located in the upper Russian River basin, applied this approach (Johnson, 2015, Figure 4). The model was applied using historical inflows assuming these represent "perfect" forecasts, and the rule curves were modified to allow a 10-day look-ahead to support release decisions for: (a) pre-release into the conservation zone if a large flood was anticipated, and (b) flood capture if a small or moderate flood were to occur but no significant threat of additional flooding

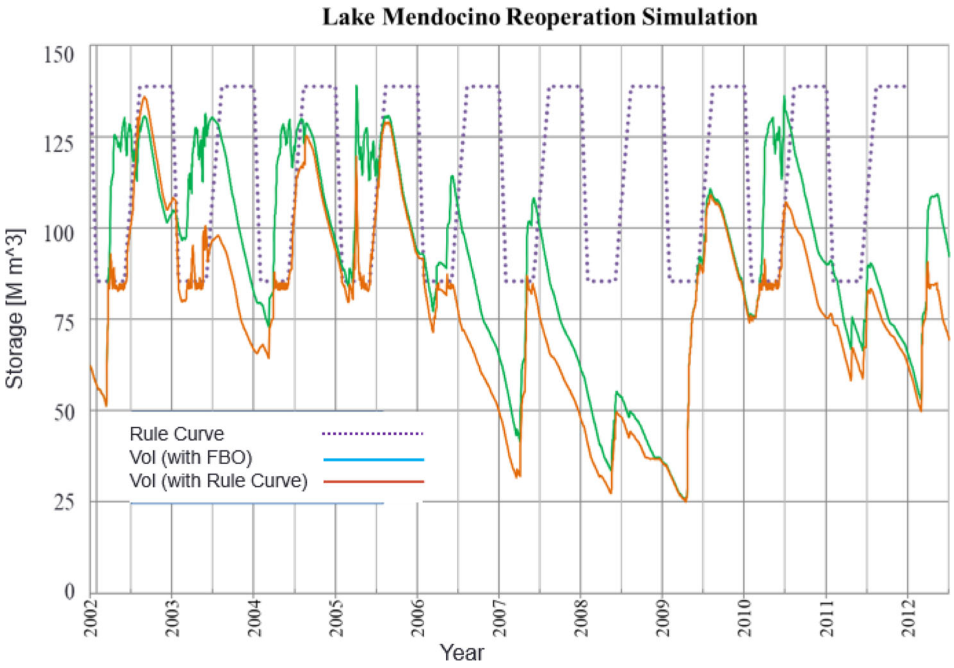

FIGURE 4 Reservoir operations simulation indicates storage increases with a forecast-based operations scheme (Johnson, 2015)

was forecast. For the 10-year period 2002 to 2012, the revised operations scheme was shown to yield an average storage increase of 12.3 M m^3/year (10,000 AF/year) over the current operations using the fixed rule curve approach. A more detailed study (FIRO, 2017) found similar results and confirmed no increase in flood risk.

The FIRO approach is being examined for other reservoirs in the region. A study for the California DWR (MBK Engineers, 2014) examined the potentials of FIRO to increase capture of water supply while maintaining flood protection. Niesar (2016) documented the potential of FIRO for Lake Del Valle in Alameda County to enhance flood control, water supply, ecosystem, and recreation services. Furthermore, the CaDWR Proposition 1 grant program is expected to expand the capacities of several reservoirs in the SF Bay area by more than 310 M m^3 (250,000 AF) to support water supply and ecosystem services (https://cwc.ca.gov/Press-Releases). Based on the Lake Mendocino analysis and a review of other reservoir storage volumes across the SF Bay region, we estimate that 31 M m^3/year (25 M AF/year) can be captured by FIRO (base case).

The values of water for municipal supply vary widely, depending on water rights, markets, and other factors. A CaDWR (2009b) report noted that as of 2006 the average price of treated water delivered to households was \$0.78/m^3 (\$960/AF). Depending on the region the price ranged from \$0.44/m^3 (\$545/AF) in the San Joaquin Valley to \$1.51/m^3 (\$1,857/AF) in the Central Coast; the SF Bay area price was \$0.96/m^3 (\$1,190/AF). These prices vary from year to year depending on hydrologic variability. For the Lake Mendocino case, using a base-level (2016) wholesale value of \$0.40/m^3 (\$500/AF), the average annual 12.3 M m^3 (10,000 AF) increase in storage would be valued financially at \$5 M per year. For the SF Bay area, a total FIRO capture of 31 M m^3/year (25 M AF/year) is valued at \$12.5 M/year. We did not assess hydropower benefits resulting from use of forecast inflows.

Water captured in reservoirs also has complementary value for ecosystem services as headwater reservoir releases to downstream treatment plants can sustain aquatic habitat, details are presented in the following.

Several water supply agencies in the SF Bay area operate facilities to recharge groundwater aquifers, and these operations can benefit from enhanced streamflow forecasts. Notable is the Santa Clara Valley Water District (SCVWD, 2016) which operates managed recharge to obtain about 74 M m^3/year (60,000 AF/year). A 10% increase in captured water directed to recharge is estimated 7.4 M m^3/year (6,000 AF/year). Sonoma and Alameda counties also have groundwater recharge programs which may benefit in a similar manner. A total base-level incremental groundwater recharge increase of 17.3 M m^3/year (14,000 AF) is estimated, valued at \$7 M/year.

4 | ECOSYSTEM SERVICES AND RECREATION

4.1 | Ecosystem services benefits

Ecosystem services are the benefits people obtain from ecosystems. Various references (e.g., CaDWR, 2008; MEA, 2005) define and classify ecosystem services into several categories including (a) provisioning services (e.g., food and water); (b) regulating services that affect floods and water quality; (c) cultural services that provide recreational, aesthetic, and spiritual benefits; and (d) supporting services such as soil formation. Weather-forecast ecosystem services were characterized by Cooter, Rea, Bruins, Schwede, and Dennis (2013), and Labadie, Zheng, and Wan (2012) applied simulation models forced by precipitation nowcasts to support recovery of salinity-sensitive biota in the St. Lucie Estuary, Fla.

Estimation of ecosystem services benefits may be based on benefits transfer approaches which involve transferring available information from studies already completed in another location and/or context (King & Mazzota, 2003). Studies to estimate the passive use value of increases in salmonid populations revealed that households are willing to pay only fractions of a penny for increases in salmon populations, but when summed across a region the total value can become several thousands of dollars per fish (Bell, Huppert, & Johnson, 2003; Loomis, 1996; Olsen, Richards, & Scott, 1991).

For this study, fisheries enhancements were valued considering potential for FIRO storage increases and releases from headwater reservoirs to provide downstream flows for spawning and sustenance. One way to assess the value is that the CaDWR Environmental Water Account water price was set at $\$0.10/m^3$ (\$125/AF) for a “critically dry” year (Herzog, 2006); the price varies depending on drought severity. As noted before, FBO reservoir operations across the SF Bay area have potential for an average annual (base-level) increase of 30 M m^3/year (25,000 AF/year). Using a price of $\$0.06/m^3$ (\$75/AF) a base level fisheries benefit of \$2 M/year is estimated for the SF Bay area.

4.2 | Water-related recreation

Hydromet forecasts support water-related recreation (boating, fishing, beach visits) by reducing threats to loss of lives and damages for hazardous events and informing recreationists of good weather supporting the activity. The use and economic benefits provided by water recreation can be substantial, although difficult to estimate (CaDWR, 2008). Kite-Powell et al. (2004), Kite-Powell, 2005a) tabulated recreational benefits as part of the PORTS® forecast system development for the Tampa Bay, FL area.

Application of a benefit transfer approach is common for general estimates of recreation values as sought here, but caution should be exercised given differences in site conditions and user characteristics. For example, various estimates of recreation user day values include \$30/day (Wiley, Leeworthy, & Stone, 2006), \$28/day (boating) to \$66/day (fishing) (Briceno & Schundler, 2015), and \$21/day (beach day-trippers) (King & Symes, 2003). Pendleton and Kidlow (2006) determined typical expenditures directly associated with beach recreation are \$25 to \$30 per beach day and generate an estimated \$15 of consumer surplus per beach day.

For the SF Bay area, we make a general estimate of water recreation benefits from AQPI forecasts based on the number of boating and beach days. There are approximately 330,000 recreational boats registered in the SF Bay region, a typical boater makes about 43 trips/year, and between 10 and 50% of the recreational boaters are aware of and make use of weather forecasts (Kite-Powell, 2005b). This translates to about 5 M boating days. An estimated 180 M to 400 M visits are made to California beaches each year (Pendleton & Kildow, 2006). Assuming San Francisco beaches are 10% of a California total of 180 M visits, yields 18 M visits. Total water recreation days are estimated to be 23 M/year. Assuming a water recreation outing generates economic surplus equal to \$20/day, the total value in the SF Bay area is \$460 M/year. If the AQPI system data leads to a 1% increase in positive recreation day experiences in SF Bay, this translates to an annual benefit from AQPI of \$4.6 M (\$0.62/person/year).

5 | WATER QUALITY

Operations of wastewater collection and treatment systems are often influenced greatly by storms, and forecasts of heavy rainfall can help to mitigate sewer inflow and infiltration, and combined sewer overflows. Capture and treatment of urban storm water and combined sewer flows is aided by hydromet forecasts, and thereby reducing water quality degradation in receiving waters.

The City and County of San Francisco has built a system of underground storage, transport, and treatment boxes to handle major rain events. Development and operation of the treatment and storage system has greatly reduced the discharge of untreated sewage and storm water to the Bay and ocean. Operation of the tank-storage system is expected to further benefit from the AQPI rainfall forecasts as the tank storage operations can be optimized to account for the spatial and temporal distribution of rainfalls. For example, Labadie, Lazaro, and Morrow (1981) analyzed the value of real-time, short-term rainfall forecasting for operation of the San Francisco North Shore Outfalls Consolidation Project. Other wastewater and stormwater management agencies in the SF Bay area have indicated that better forecasts could benefit their operations. Benefits for water quality are not estimated here except to note that significant value is expected.

6 | TRANSPORTATION

The transportation sector can be highly weather dependent, and all different transport modes (road, air, sea, rail, inland waterways) are relevant. Extreme weather events, especially when exacerbated by sea-level rise, will cause high-water levels and sizable wind waves (Biging, Radke, & Lee, 2012; Cayan et al., 2008; Kahrl & Roland-Holst, 2008).

6.1 | Roadways

Road transport has become increasingly weather reliant. In the SF Bay area, Bromirski and Flick (2008) documented the hundreds of millions of dollars in storm and flood damage in the SF Bay Region in 1997–1998. Others have documented weather related costs and forecasts benefits, including Smith and Vick (1994) and Nurmi, Perrels, & Nurmi, 2013.

Enhanced weather forecasts may guide road travel choices on timing and routes; although most drivers do not change. Enhanced weather forecasts could save $0.50/person/year (Nurmi et al. (2013). For the AQPI system, an incremental value $.10/person/year is assumed. Base level benefits for roadways are estimated to be $0.77 M/year.

6.2 | Aviation

Airport terminal weather forecast accuracy has been identified as a key factor in delays (e.g., Klein, Kavoussi, & Lee, 2009). By lowering the probability of costly wrong decisions, meteorological information generates direct economic benefits for the airlines. A study of the value of weather forecast for Zurich airport placed forecast value at $12 M to $18 M (Gruenigen, Willemse, & Frei, 2014); given approximately 25 M passengers, the value is about $0.50/passenger. Taking the three major airports in the SF Bay area total passengers were about 80 M (55 M, 12.5 M, 13 M) in 2017 ("Air Traffic Statistics". flySFO.com). At $0.50/passenger/year, the total forecast benefits are about $40 M/year. Leigh (1995) estimated that a 1% increase in forecast accuracy would result in a ~10% increase in value. Assuming a 2% increase in value ($0.01/person/year) associated with the AQPI forecasts, the base level benefits are estimated to be $0.8 M/year.

6.3 | Rail

Benefits of advanced forecasts for rail transportation are characterized in similar manner using costs avoided for delays. The BART system in the SF Bay area has a weekday ridership of 374,000 persons and has direct connections to two regional rail services: Caltrain, which provides service

TABLE 3 Metrics and estimated base-level benefits of the AQPI system

Source of Benefits	Method	Data	Confidence level	Benefit ($M/year)
Flood mitigation	Increased lead time allows reduction of damages.	10% reduction, $50 K contents, 75% response. (#structures, EAD$)	Moderate	$29
	Subtotal for flood mitigation		Moderate	$29
Water supply	Captured water anticipating AR event at 10 days lead time.	Base value $0.40/m^3 ($500/AF). (1.23 M m^3 (1,000 AF) captured)	Moderate	$12.5
	Captured water for aquifer recharge.	Base value $0.81/m^3 ($1,000/AF). (1.23 M m^3 [1,000 AF] captured)	Low	$7
	Subtotal for water supply		Moderate	$19.5
Ecosystem enhancement and water-related recreation	Fishery flows enhanced by FBO reservoir capture.	Base value $0.06/m^3 ($75/AF). (1.23 M m^3 [1,000 AF] captured)	Moderate	$2
	Reduce risks and delays for water recreation.	Based on population; Base value at $0.60/person/year (population in 1000s)	Low	$4.6
	Subtotal for ecosystem and recreation		Low	$6.6
Transportation	Enhanced weather forecasts guide road travel on timing and routes.	Base value $.10/person/year. (population 1000s)	Moderate	$0.8
	Aviation flight scheduling enhanced by weather information.	Avoid delays; Base value $0.01/passenger (passengers in Ms/year)	Low	$0.8
	Rail infrastructure, and safe and timely travel.	Avoid delays; Base value $0.05/person/year (population in 1000s)	Low	$0.4
	Shipping benefits include safety, efficiency, and lower insurance.	Avoid delays and groundings; Base value $0.50/person/year (pop. 1000s)	Low	$3.8
	Subtotal for transportation		Low	$5.8
Total incremental benefits from enhanced forecasts ($M/year)			Moderate	$61

between San Francisco and San Jose, and Amtrak's Capitol Corridor, which runs from Sacramento to San Jose. Like roads, for the AQPI system an incremental value $0.05/person/year is assumed for the nine-county SF Bay area population (7.8 M), leading to base level benefits for rail of $0.4 M/year.

6.4 | Ports

Formal economic procedures were applied by Kite-Powell (2005a), Kite-Powell, 2005b) to estimate direct benefits of near-real time forecasts about water levels and currents at specific points in Tampa Bay. Benefits of the PORTS® study were summarized as high confidence benefits at $2.4 M/year to $4.8 M/year; lower confidence benefits at $2.2 M/year, and potential or speculative benefits at $2.2 M/year; total estimated quantifiable benefits were $6.6 M/year to $9.0 M/year. Given a population of 1 M in the Tampa Bay area, this translates to $6 to $9 per person per year. For storm surge forecasts, Kite-Powell (2005a, 2005b) estimated an annualized risk of $50 M/year. Applying a 1% rubric (Kite-Powell, 2005b), they estimated an additional annualized value of $500,000/year ($0.50/person/year) from improved storm surge prediction. Using this assumption, we estimate base level benefits for ports to be $3.8 M/year.

TABLE 4 AQPI system benefits by category

	AQPI base-level benefits		
Benefit category	**($M/year)**	**PV ($M)**	**(%)**
Flood mitigation	$29.1	$214.1	47.7%
Water supply	$19.5	$143.5	32.0%
Ecosystem	$2.0	$14.9	3.3%
Recreation	$4.6	$33.9	7.5%
Trans - roads	$0.8	$5.7	1.3%
Trans - air	$0.8	$5.9	1.3%
Trans - rail	$0.4	$2.8	0.6%
Trans - port	$3.8	$28.3	6.3%
Total	$61.0	$449.1	100%
Initial cost	$66.0		
Annual cost	$3.3	$90.3	
B/C ratio	5/1		

7 | BASE-LEVEL BENEFITS SUMMARY

The base-level incremental benefits tabulation (Table 3), based on best-estimate factors, totals to $61 M/year. The estimates are assigned an overall confidence level of moderate; some categories have low confidence. Assignment of moderate and high confidence are made given detailed analysis specific to the SF Bay area. Low confidence is assigned given limited data involved, such as with transfer of benefits. Assuming a 10-year economic life and a 6% discount rate, the present value of the annual benefits total to $449 M. This compares to $90 M in present value costs associated with AQPI. The base-level benefit/cost ratio is 5/1. Taken by category (Table 4) 48% of the benefits are for flood damage mitigation ($29.1 M/year), water supply ($19.5 M/year, 32%), ecosystem ($2 M/year, 3%), recreation ($4.6 M/year, 8%), and transportation ($5.8 M/year, 9%). The largest portion of the transportation benefit is for shipping (6%).

Taken by county, benefits for Santa Clara and Sonoma counties account for about one-half of the total for the

TABLE 5 Sensitivity analysis summary

Benefit category	**Variable**	**Base-level**	**High-level**	**Low-level**
Flood damage reduction	Household contents ($)	$50,000	$75,000	$25,000
	% damage reduction (incremental)	10.0%	15.0%	5.0%
	Response efficiency (%)	75%	90%	50%
Water supply	FBO water supply (m^3, AF)	24 M (25,000)	48 M (40,000)	12 M (10,000)
	Water value ($/m3, $/AF)	$0.41 ($500)	$0.81 ($1,000)	$0.20 ($250)
Ecosystem services	FBO fish water ($\$/m^3$, $/AF)	$0.06 ($75)	$0.10 ($125)	$0.02 ($25)
	Water recreation ($/person/year)	$0.62	$1.20	$0.30
Transportation	Highways ($/person/year)	$0.10	$0.25	$0.05
	Airports ($/person/year)	$0.01	$0.05	$0.005
	Trains ($/person/year)	$0.05	$0.15	$0.02
	Ports ($/person/year)	$0.50	$1.00	$0.25
Total incremental benefits ($M/year)		$61.0	$118.4	$29.1
B/C ratio		5/1	10/1	2/1

region. For Santa Clara County, the major benefits accrue for flood damages avoided, while for Sonoma County the major benefits are for water supply obtainable with forecast-informed reservoir operations.

For the SF Bay region, these base-level incremental benefits equate to about $8 per person per year. The annual cost is $1.60/person/year. For comparison to current practice, an average annual household value of $286 is placed on weather information (NWS, 2011). Assuming 2.5 persons per household, the incremental value of the AQPI system is $20 per household, which is an increase in value on the order of 7%.

The benefit estimates presented above represent a "base case" or best estimate. It is of interest to examine how sensitive the estimates are to variations in the input factors. Table 5 lists the factors used for the sensitivity analysis, and the values assigned for the Base-Level, High-Level (optimistic), and Low-Level (pessimistic) scenarios. The total incremental benefits ranged from the base case ($61 M/year) up to $118 M/year (high) and down to $29 M/year (low). These translate to benefit/cost ratios of 5/1 (base), 10/1 (high), and 2/1 (low).

8 | CONCLUSIONS

AQPI is shown to have enormous potential to add significant economic value to the SF Bay region through improved hydrometeorological forecast, warning, and response. Conservative estimates of benefits significantly out-pace system costs. Reconnaissance-level estimated B/C ratios range from 2/1 to 10/1.

AQPI integrates a sequence of advanced technologies, including (a) satellite detection and tracking of storms, (b) new gap-filling radars, (c) NWP modeling, (d) distributed hydrologic modeling of watersheds, and (e) coastal flood inundation modeling.

Benefits are derived from a spectrum of human and ecological activities in which SF Bay area residents participate, including avoidance of flood damages, maximizing water supplies, and enhancing ecological, recreational, and transportation services.

It is important to acknowledge that many of the benefits are dependent on appropriate and adequate response by the hazards and water resources management agencies and citizens. To maximize response "efficiency," the AQPI project involves designing and delivering the storm forecasts and warnings to meet user needs, and conducting training and "table top" exercises to establish understanding and preparedness.

ACKNOWLEDGEMENTS

This work was supported by the National Oceanic and Atmospheric Administration (NOAA) Office of Oceanic and Atmospheric Research (OAR), and the NOAA Earth System Research Laboratory (ESRL) Physical Sciences Division. Mention of a commercial company or product does not constitute an endorsement by NOAA/Earth System Research Laboratory. The findings and conclusions on this report are those of the authors and do not necessarily represent the views of NOAA or the National Weather Service.

CONFLICT OF INTEREST

There is no conflict of interest by the authors involved in this project.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Johnson LE, Cifelli R, White A. Benefits of an advanced quantitative precipitation information system. *J Flood Risk Management*. 2020;13 (Suppl. 1):e12573. https://doi.org/10.1111/jfr3.12573