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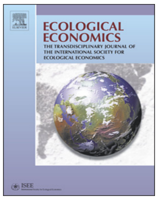

Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT

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ABSTRACT

Functioning ecosystems can buffer communities from many negative impacts of a changing climate. Flooding, in particular, is one of the most damaging natural disasters globally and is projected to increase in many regions. However, estimating the value of "green infrastructure" in mitigating downstream floods remains a challenge. We estimate the economic value of flood mitigation by the Otter Creek floodplains and wetlands to Middlebury, VT, for Tropical Storm Irene and nine other floods. We used first principles to simulate hydrographs for scenarios with and without flood mitigation by upstream wetlands and floodplains. We then mapped flood extents for each scenario and calculated monetary damages to inundated structures. Our analysis indicates damage reductions of 84–95% for Tropical Storm Irene and 54–78% averaged across all 10 events. We estimate that the annual value of flood mitigation services provided to Middlebury, VT, exceeds $126,000 and may be as high as $450,000. Economic impacts of this magnitude stress the importance of floodplain and wetland conservation, warrant the consideration of ecosystem services in land use decisions, and make a compelling case for the role of green infrastructure in building resilience to climate change.

1. Introduction

Ecosystems support human well-being in myriad ways. In many places, human activities have altered ecosystems to such an extent that real consequences on well-being are apparent (Millennium Ecosystem Assessment, 2005). To respond to these changes, the focus of conservation is broadening to include not only the negative impacts that people have on nature but also the benefits nature provides to people (Daily et al., 1997; Fisher et al., 2009). These benefits, or ecosystem services, include the many ways in which our communities and economies rely on functioning natural landscapes (Kareiva et al., 2011). Such services have real and quantifiable value, although they are largely unrecognized externalities in our economy (Goulder and Kennedy, 2011). Economic valuation of ecosystem services can be instrumental in decision making that incorporates the contributions of nature to human well-being (Daily et al., 2009).

One way that ecosystems support well-being is by providing resilience to climate change. For example, coastal ecosystems can buffer against impacts from severe storms (Costanza et al., 2008; Barbier et al., 2008; Gedan et al., 2011; Arkema et al., 2013); diverse ecosystems provide natural checks that limit the spread of infectious diseases (Keesing et al., 2010); and freely flowing rivers can alleviate the impacts of severe storms and flooding expected as climate changes (Palmer et al., 2008). Increasingly, "green infrastructure," the network of functioning ecosystems that confer benefits to people (Benedict and McMahon, 2012; Tzoulas et al., 2007), is recognized as a method of building climate resilience (Gill et al., 2007), that may be more cost-effective than engineered solutions in many cases (Benedict and McMahon, 2002; Turner et al., 2007).

In particular, floods cause more human fatalities than any other natural disaster (Bates et al., 2008; Murray et al., 2013) and are the most frequent natural disaster in many regions (Bates et al., 2008). The potential of wetlands and floodplains to reduce flooding is widely recognized. Wetlands are areas where water is the primary factor driving plant and animal life (Zedler and Kercher, 2005). Floodplains are the flat lands adjacent to rivers created by their lateral migration (Acreman et al., 2003). Both can act as green infrastructure to mitigate flooding by storing and slowing floodwater so that it arrives downstream gradually rather than in a single large pulse (Assessment, M.E., 2005; Bullock and Acreman, 2003). Wetlands are thought to be most effective in reducing small, frequent flood events (Interagency Floodplain Management Review Committee United States, 1994), whereas floodplains can reduce downstream peak flows for more severe events as well (Acreman et al.,

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2003; Opperman et al., 2009). Many climate scenarios indicate an increase in severe precipitation events (Min et al., 2011), which suggests that the importance of wetlands and floodplains for human well-being will increase.

Despite the importance of wetlands and floodplains for alleviating floods, both have undergone widespread loss resulting from human interference with river geomorphology, such as the construction of levees and river channelization (Zedler and Kercher, 2005; Tockner and Stanford, 2002). These practices promote incision and disconnection of rivers from their floodplains and associated wetlands. By rapidly channeling water downstream, these hard engineering solutions reduce flooding locally but can increase floods downstream (Hey and Philippi, 1995; Wharton and Gilvear, 2007). Both wetland loss and floodplain disconnection are being targeted by conservation and restoration projects with green infrastructure goals. The non-market benefits of wetlands and floodplains are often undervalued or completely unaccounted for in local decisions (Assessment, M.E., 2005) because these benefits are externalities that mostly accrue downstream. Quantifying the economic value of flood mitigation services, in terms of real and avoided flood damages, can influence regional-scale planning decisions regarding the use of green and built infrastructure (Lambert, 2003) by connecting upstream decisions to downstream impacts. In order to responsibly allocate conservation resources to protect wetlands and floodplains, we need to know when expected returns on that conservation investment will be positive.

Current techniques to quantify water-related ecosystem services generally fall within three categories. First, empirical approaches are used to measure the biophysical supply of services, such as measuring the water storage capacity of wetland soils (Ming et al., 2007) or relating the development of wetlands to flooding frequency (Brody et al., 2006). Second, advanced hydrological models are modified to inform ecosystem service decisions; however, these models do not tend to produce results necessary to evaluate benefits to specific stakeholders (Keeler et al., 2012). Finally, models developed as support tools for ecosystem service decision making seek to provide more direct measures of human well-being outcomes (Sharp et al., 2014; Villa et al., 2009). There are existing hydrologic models and empirical approaches that measure the impacts of land use on flooding (Ming et al., 2007; Brody et al., 2006; Neitsch et al., 2011; Liang et al., 1994; Feldman, 2000) and other models that measure the impacts of flooding on people (FEMA, 2003), but we do not know of an existing model designed for ecosystem service decision making. Although it may not be possible to consider biophysical and socioeconomic dynamics each in depth, it is crucial that valuations of hydrologic services consider both (Brauman, 2015).

We present a first-order approach to estimating the value of flood mitigation services provided by wetlands and floodplains built upon ecologic, hydrologic, and economic principles. Our approach is novel in linking biophysical flooding dynamics to human beneficiaries at the watershed scale. To illustrate this approach, we quantify the economic value of flood mitigation in terms of avoided damages to human beneficiaries provided by the wetland–floodplain complex of the Otter Creek (which remains highly connected to its floodplain and associated wetlands) to Middlebury, Vermont (USA). Specifically, we address two questions:

1) What was the value of the Otter Creek wetlands and floodplains in reducing flood damage during Tropical Storm Irene in 2011?
2) Beyond this single event, what is the expected annual value of the wetlands and floodplains in mitigating flood damages?

These valuations allow us to quantify the damages of a high-profile storm that has focused attention on role of wetlands and floodplains in bolstering climate resilience, and to estimate the damages avoided in an average year. The latter is more likely to be actionable information for decision makers than the damage costs of a rare event, although both are important given that storm intensity and rainfall are increasing in this region (Galford et al., 2014). This work enables explicit consideration of flood mitigation by wetlands and floodplains in land use and resource decisions.

2. Methods

We estimated the value of flood mitigation services as the damage to downstream communities that was avoided as a result of wetlands and floodplains. Quantifying avoided damages is a well-established method of non-market valuation (De Groot et al., 2002; Farber et al., 2002). Specifically, we estimated the difference in expected damages between current conditions (where the river is connected to wetlands and floodplains, hereafter referred to as the “wetlands” scenario) and two hypothetical scenarios where the river does not have these connections. One of these counterfactual scenarios represents a large effect of wetlands and floodplains (“no-wetlands high” scenario) and the second represents a more conservative effect (“no-wetlands low” scenario). These scenarios apply theoretical conditions to the Otter Creek to illustrate the potential range of benefits provided by the wetland–floodplain complex, rather than predicting the precise value of those benefits. More advanced process-based modeling would be appropriate if specific predictions were needed given expected marginal changes in access to wetlands and floodplains. The use of scenarios is a well-established method of illustrating the envelope of possible outcomes given large uncertainties (Soares-Filho et al., 2006).

To evaluate flood damages, we followed a five-step process: First, we modeled hypothetical flood peaks representing conditions where the Otter Creek lacks connection to its floodplain and wetlands (henceforth referred to as “no-wetlands” scenarios for simplicity). Next, we estimated flood extent for wetlands and no-wetlands scenarios. Third, we identified flooded structures in each scenario. Fourth, we calculated expected damages for each structure as a function of flooding depth and house value. Finally, we estimated the value of avoided damages by pooling costs for each scenario and calculating the difference in total damage between wetlands and no-wetlands scenarios. We followed these steps for Tropical Storm Irene and for nine additional historic flooding events in order to estimate the annual value of flood mitigation.

2.1. Study System

We focused on Otter Creek in Middlebury, VT (Fig. 1). The Otter Creek is a useful case study for several reasons. First, Vermont's land use pattern, with development concentrated along rivers in low-lying floodplain areas, is typical of many rural regions. Second, recent extensive flood damages related to very large storms have pushed flood resiliency forward as a priority in Vermont and the Northeast. Finally, climate projections estimate that precipitation will increase and will more often occur in high energy precipitation events, a trend that has already been observed over the last half century (Galford et al., 2014; Guilbert et al., 2014). This indicates that flood resiliency will increase in importance. Finally, the Otter Creek remains well connected to its floodplain, and thus has the potential to illustrate the value of maintaining functional access to floodplains and wetlands for the purpose of mitigating floods.

Otter Creek flows north through a large wetland complex and a relatively wide, connected floodplain from Rutland, VT, to the town of Middlebury (Fig. 1). Although three-quarters of Vermont streams and rivers are incised and thus disconnected from their floodplains (Kline and Cahoon, 2010), stream geomorphic assessment indicates that there is virtually no stream incision on the main stem of Otter Creek (Consulting, S.M.R.a., 2006). The watershed is predominantly forested (60%), 5% of land cover is developed, 24% is agricultural, and 8% is wetland. Wetlands comprise a total of 18,000 acres, most of which are forested swamplands. USGS gauging stations on the Otter Creek are positioned in the towns of Rutland (hereafter, “upstream”) and Middlebury (hereafter, “downstream”). The river meanders 36 river miles between the gauges, and elevation change is modest, dropping from 475 to 336 ft above sea level (U.S. Geological Survey, 2012). The downstream gauge has a drainage area twice as large as the upstream gauge (628 vs 307 mile^2). The paired gauges record flow dynamics during rain events

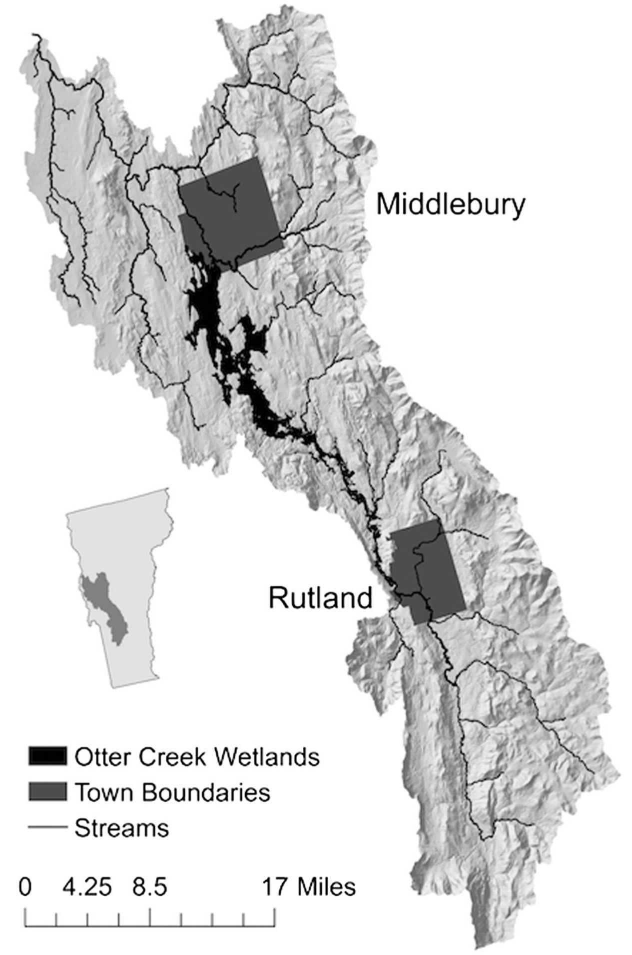

Fig. 1. Map of the Otter Creek watershed. The Otter Creek flows northward from Rutland to Middlebury.

and enable us to value flood mitigation provided by the wetland–floodplain complex in the absence of an advanced hydrological model.

Tropical Storm Irene hit Vermont on August 28, 2011. Every town in Vermont reported flood damages (Galford et al., 2014), including Rutland and Middlebury. Rutland experienced the highest peak flow on record on August 28th and suffered serious flood damages over the five days following the storm. Roughly thirty miles downstream and a week later, Middlebury experienced a much lower peak and flooding was minor because floodwater arrived gradually over a longer time interval (several weeks instead of about five days) (Fig. 2). Locally, the observed difference in flood damage was touted as an example of flood mitigation by wetlands and floodplains, and of green infrastructure bolstering the resiliency of local communities to extreme rain events (Marangelo, 2011). We focus our valuation on the town of Middlebury itself, which encompasses 14 mile^2 and has a population of roughly 6600 (U.S. Cenus Bureau).

A hydrograph is a plot of discharge as a function of time—typically in cubic feet per second (CFS). We accessed hydrographs for upstream and downstream gauges over the interval of the downstream storm water pulse (17:00, 8/27/11 to 11:00, 9/22/11) (U.S. Geological Survey, 2012) (Fig. 2). We included a long tail on the hydrograph's falling arm to ensure a conservative estimate of the pulse duration and magnitude. (The falling arm is where discharges of the two hydrographs are most similar.) Flood volume is the sum of areas area under the hydrograph curve. We calculated volume as a Reimann sum:

$$V = \sum_{i=0}^{n-1} q_i * \Delta t \tag{1}$$

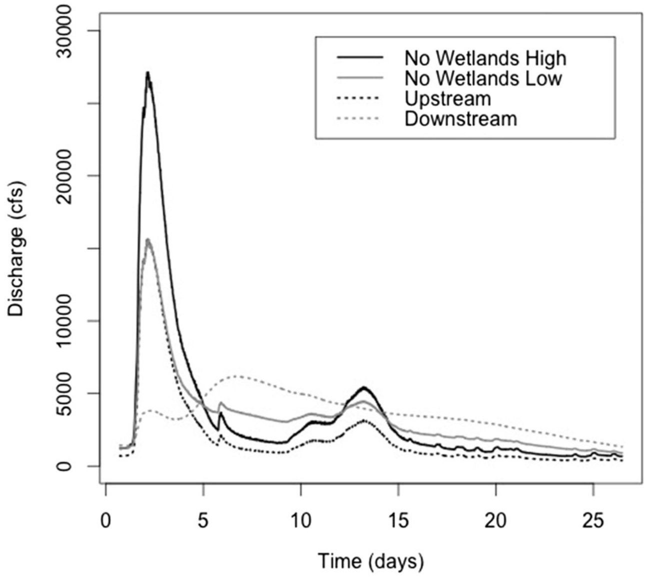

Fig. 2. Observed and modeled hydrographs for Otter Creek, VT.

where V is total water volume in cubic feet, q is discharge (cfs) for each time interval i, and Δt is the time between discharge measurements at the gauge (15 min).

2.2. Modeling Peak Flows

We developed two scenarios to estimate peak flows in cases where wetlands and floodplains were eliminated completely. Although the Otter Creek is not under immediate risk of losing its wetlands or its connection its floodplain, such losses are common elsewhere and reduce the capacity of landscape to mitigate downstream flooding. Further, "total loss" scenarios such as these are needed to determine the ecosystems' total value for flood mitigation. Our two no-wetlands scenarios differ in terms of the size of the impact that disconnection from wetlands and floodplains has on downstream flooding, By providing a high and low estimate of this effect, they illustrate the range of effects wetlands and floodplains may have on downstream flood damages.

2.2.1. No-wetlands High Scenario

The no-wetlands high scenario represents a case where the difference in the shape of the upstream and downstream hydrographs (the timing of floodwater arrival) was solely attributable to the wetlands and floodplains that lie between the two gauges, but where the wetlands and floodplains had no impact on the total floodwater volume.

We normalized the upstream hydrograph by dividing the volume for each time interval by the total upstream water volume, and then multiplied these incremental volume measures by the total volume recorded at the downstream gauge:

$$v_{i_{\text{No-wetlands high-impact}}} = \frac{v_{i_{\text{Upstream}}}}{V_{\text{Upstream}}} * V_{\text{Downstream}} \tag{2}$$

where v is water volume for a time interval i, and V is total water volume.

By modeling the no-wetlands hydrograph using the upstream hydrograph shape and downstream floodwater volume, we simulated a case that does not allow for any dissipation of the storm peak or temporary water storage by the landscape, but that does contain all the rainfall that occurred between the upstream and downstream gauges. In doing so, we also assumed that much of the water entering between the gauges would contribute to the downstream hydrograph peak. Essentially, this simulated a case in which floodwater moved downstream through an impervious channel, and where all of the water that fell between the upstream and downstream gauges entered the channel exactly in proportion to the passing flood peak. Because of these non-conservative assumptions, this scenario represents an upper bound on the value of the wetland–floodplain complex.

2.2.2. No-wetlands Low Scenario

We created a more conservative scenario that differed from the no-wetlands high scenario in two ways. First, we assumed wetlands and floodplains only affected water that entered the Otter Creek above the upstream gauge. To model this, we assumed water entering the Otter Creek between the gauges did so with timing proportional to the downstream hydrograph (instead of proportional to the upstream hydrograph). We calculated the difference in observed water volumes recorded at the upstream and downstream gauges using Riemann sums, multiplied the volume of water that entered the channel between the two gauges by the normalized downstream hydrograph, and multiplied the upstream water volume by the normalized upstream hydrograph. This assumption causes us to underestimate the impact of the wetland–floodplain complex, thus this scenario represents a lower bound on their value.

Second, wetlands and floodplains were considered to be only partially responsible for flood mitigation. Floodwaters would have dissipated to some extent due to factors other than wetlands and floodplains. Others have shown that wetlands are the only land cover type that impacts flood peaks in this region (Olson and Veilleux, 2014). However, topographic effects other than floodplains such as storage and friction within the channel will also reduce flood peaks, so that larger drainage basins tend to have lower flood peaks relative to their flood water volume even when they do not have floodplain access. To account for these effects, we regressed discharge per unit area against drainage basin size for 10-year floods at Vermont USGS gauges (Fig. S1, Olson and Veilleux, 2014). Using this relationship, we determined that the unit discharge expected for the drainage area of the downstream gauge was 11% lower than that expected for the drainage area of the upstream gauge. We decreased the volume of the upstream hydrograph for each time interval by this dissipation factor. Because most rivers in Vermont have been disconnected from floodplains through incision, this dissipation factor provides us with an estimate of how much the flood peak would dissipate while traveling downstream from the upstream to the downstream gauge in the absence of wetland and floodplain effects. In sum, the no-wetlands low hydrograph was calculated as:

$$v_{i_{\text{No-wetlands low}}} = \left(\frac{v_{i_{\text{Upstream}}}}{V_{\text{Upstream}}} * V_{\text{Upstream}} * 0.89\right) + \left(\frac{v_{i_{\text{Downstream}}}}{V_{\text{Downstream}}} * V_{\text{Between}}\right) \tag{3}$$

Where v is water volume for a time interval i, and V is total water volume, as above.

Although this is a much more conservative estimate of the potential impact of wetlands and floodplains on peak flows, it does not represent an absolute lower bar of that affect.

2.3. Determining Flood Extent

For each scenario, we used a rating curve built from a log–log regression of the highest daily mean water level for every year from 1927 to 2012 ($r^2 = 0.96$, $p < 2.2e-16$; Fig. 3) to relate discharge (cfs) to stage (river height, feet). From the rating curve, we calculated the flood elevation associated with downstream peak discharge from the wetlands and no-wetlands hydrographs. While many of the annual peaks in our data set represented cases where Otter Creek overflowed its channel and inundated the surrounding floodplain, the no-wetlands discharge exceeded all recorded annual peaks so we were forced to extrapolate beyond our data to determine flood elevation.

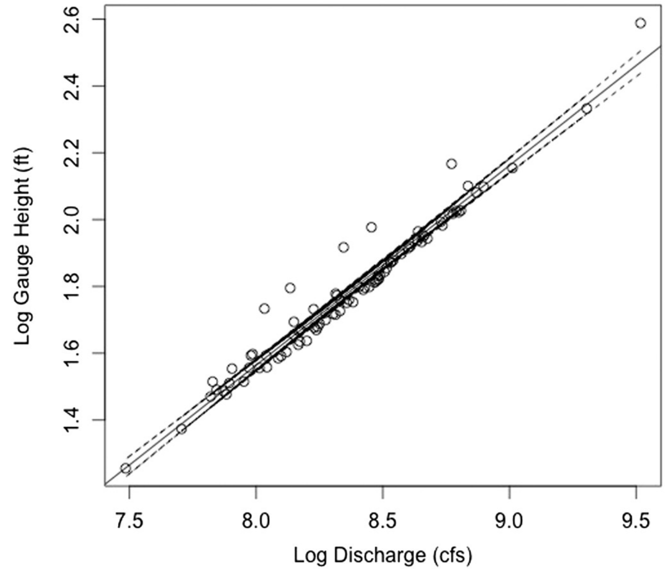

Fig. 3. Rating curve relating discharge and flood height at the downstream gauge ($r^2 = 0.96$, $p < 2.2e-16$).

A 15-m waterfall occurs in Otter Creek at Middlebury just below the downstream gauge. Thus, we adjusted flood heights for areas below the falls (north) by subtracting 15 m (Fig. S2) but otherwise assumed that the rating relationship and flood elevation were equal throughout Middlebury (i.e., a “bathtub” model of flooding). In reality water volume, not height is conserved as a flood pulse travels downstream because the relationship between volume and height is sensitive to floodplain geometry. The benefit of this assumption was the use of a single metric, flood height, which could be robustly estimated (Fig. 3).

We defined the flood extent as areas in Middlebury that were hydrologically connected to the Otter Creek and that fell below the flood elevation. This flood extent was identified using a high-resolution 1-m digital elevation model (DEM) derived from LiDAR data acquired under leaf-off conditions in 2014.

2.4. Identifying Flooded Structures

We overlaid the flood extents for each scenario with a point database of Middlebury's structures that was created for emergency response efforts (E911 Board, 2013). Structures were determined to be flooded if they fell within the flood extent, or if they fell within a 100 ft. buffer of the extent and were within two feet of the flood elevation. The latter criterion accounts for structures above the flood level with basements that may have flooded. The Federal Emergency Management Agency estimates monetary damages beginning with flood depths of −2 ft for residential structures (FEMA, 2003), and most homes in Vermont have basements. We calculated each structure's flooding depth as the structure's ground elevation, as determined by the LiDAR DEM, subtracted from the flood elevation.

All hydrograph manipulations and flood elevation calculations were performed using R statistical software (R Development Core Team, 2010). Flood extent scenarios were performed in Quick Terrain Modeler (Imagery, 2014). All other GIS analyses were done using the ArcGIS software package (ESRI (Environmental Systems Resource Institute)).

2.5. Monetary Damages

We calculated expected damage for each structure as a function of flooding depth and property value (Fig. 4). We applied a depth-damage function for residential structures with basements from FEMA's HAZUS guidelines (FEMA, 2003). This function is developed from national insurance claims, with adjustments for uninsured losses. We merged a publicly available database of property tax records with the spatial data set of structures. The matching of these data sets had to be verified and cleaned by hand due to discrepancies such as spelling errors and duplicated entries. We also verified and, in some cases, updated property estimates from Zillow (Zillow Inc., 2013). Publicly owned structures with no tax record were assigned the lowest property value of the identified flooded structures.

2.6. Valuation of Avoided Damages

We calculated the value of flood mitigation services provided to Middlebury by the upstream wetlands and floodplains as the difference in total damages for all structures between the wetlands and no-wetlands scenarios.

2.7. The Mean Annual Value of Flood Mitigation

The method outlined above resulted in an estimate of avoided damages for a single event, Tropical Storm Irene. To quantify the annual expected avoided damages, we repeated the procedure for Irene and nine additional flooding events using historical data. Prior to 2007, discharge data were shown as mean daily values rather than in 15-min intervals. We obtained these hydrograph data for the seven largest events on record at the upstream gauge (including Tropical Storm Irene), plus three floods whose peak discharge approximated those of two-year and five-year floods (Olson & Bent). For each storm event, we included data for one month before and one month following the upstream flood peak.

Using wetlands and no-wetlands damage estimates for these ten events, we determined mean annual value by establishing a probability-damage function that relates expected damages to annual exceedance probability, paralleling the methodology of the U.S. Army Corps of Engineers for risk analysis (National Research Council, 2000). Annual exceedance probability, p, is the probability that a discharge Q is equaled or exceeded in a given year, and is the reciprocal of the return interval. For example, a flood expected to occur approximately every 20 years has an exceedance probability of 0.05, i.e., a 5% chance of occurring in any given year. We fitted an exponential decay function to the peak discharge of FEMA designated 2-, 5-, 10-, 25-, 50-, 100-, and 500-year floods (Olson & Bent) and used this function to determine the annual exceedance probability of each flood we modeled, based on downstream discharge in the wetlands scenario. Finally, we created damage probability functions by fitting negative exponential curves to the expected damage against exceedance probability for each historic flood and for both wetlands and no-wetlands scenarios.

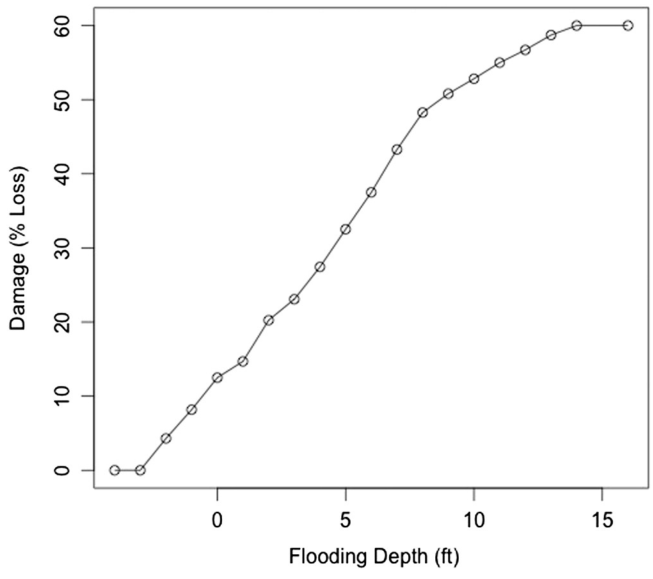

Fig. 4. Depth–damage curve used to relate flood depth of flooded structures to percent loss of the structure value due to flood damages (FEMA, 2003).

We estimated expected annual damages as the integral of the probability-damage function over the range of exceedance probabilities from zero to one and determined the mean annual value of flood mitigation services as the difference in expected annual damages between the wetlands and no-wetlands scenarios.

2.8. Net Present Value Calculation

We calculated net present value based on this average annual value of flood mitigation benefits by assuming that this value will be accrued in perpetuity and that future values are discounted relative to present value. We applied a range of plausible discount rates: the standard U.S. discount rate for water resource decisions is 3.375% (U.S. Bureau of Reclamation, 2014). This rate is lower than the standard discount factors used by FEMA (4.125%) (FEMA, 2003) and the U.S. Army Corps of Engineers (7%) (McIntyre et al.). However, it is much higher than discount rates applied to long term environmental benefits elsewhere, such as the declining discount rate suggested by the UK Treasury (Turner, 2007), and the 1.4% discount rate adopted by the Stern Review on the economics of climate change (Stern and H.M.s. Treasury, 2006).

We compared these estimates of net present value to the costs of conservation by assuming these costs are equal to the costs of purchasing all 18,000 acres of Otter Creek wetlands for the county average value of farmland ($3044 and $2718 per acre in Addison and Rutland counties, respectively) (National Agricultural Statistics Service, 2014).

3. Results

Middlebury's peak discharge for Tropical Storm Irene in the wetlands scenario corresponds to a flood height of 7.4 ft. above the downstream gauge (Table 1). By contrast, our modeled no-wetlands scenarios indicate flood heights of 13 to 18 ft. above the gauge and greatly expanded flood extents. We identified 21 to 54 flooded structures in the no-wetlands scenarios, compared to just nine in the wetlands scenario (Fig. 5). The total damages for all flooded buildings was $100,600 in the wetlands scenario, which is similar to the $70,000 in actual reported damages in Middlebury (Middlebury, Vermont Single Jurisdiction All-Hazards Mitigation Plan Working Draft, 2014). We estimate damages of $626,600 to $1,900,800 in the no-wetlands scenarios (Table 1). These differences correspond to an 84–95% reduction in financial cost of floodwater inundation and between $525,900 to $1,800,200 in avoided damages.

Expected damages across the 10 modeled floods ranged from $45,000 to $338,000 in the wetlands scenario, and from $130,400 to $1,339,000 in the no-wetlands scenarios (Table 2). The average damage reductions were 54% to 78% for low and high scenarios, respectively. Reductions tended to be greater for smaller, more frequent floods (Fig. 6). For each scenario, we fit probability-damage functions to these ten events. Based on these damage functions, we calculated expected annual damages to be $75,000 in the wetlands scenario, $201,400 in the no-wetlands low scenario, and $534,000 in the no-wetlands high scenario (Fig. 7). The mean annual value of flood mitigation services provided to Middlebury is therefore $126,000 based on our low scenario, and $459,000 based on our no-wetlands high scenario.

By applying the U.S. standard discount rate for water resource decisions (U.S. Bureau of Reclamation, 2014) to our high estimate of annual flood mitigation value, we estimate that the net present value (NPV) of mitigation services exceeds 12 million dollars, which is over a quarter of our estimated costs of conservation (Table 3). Using the declining discount rate suggested by the UK Treasury, NPV rises to approximately 16 million dollars, or 30% of the costs of conservation. Using the 1.4% discount rate adopted by the Stern Review on the economics of climate change (Stern and H.M.s. Treasury, 2006), NPV triples and amounts to over 60% of land acquisition costs. When we apply a discount rate

Table 1
Comparative summary of peak flows, flood height above the gauge, flooded structures, and expected damages following Tropical Storm Irene.

Scenario	Peak discharge (cfs)	Flood height (feet above gauge)	Structures affected	Expected damages
Wetlands	6180	7.4	9	$100,600
No-wetlands low estimate	15,600	12.8	21	$626, 600
No-wetlands high estimate	27,100	17.9	54	$1,900,800

back-calculated from mean agricultural land values and rents (Stern and H.M.s. Treasury, 2006) (i.e., assuming rents reflect annual benefits accrued in perpetuity), this value rises to 95% of conservation costs (Table 3). Using our low estimate of flood mitigation values and these same discount rates and cost estimates, we find that net present values range from $1,800,000 to $14,000,000, which is 3–27% of our estimated costs of conservation.

4. Discussion and Conclusions

We show that wetlands and floodplains can provide valuable flood mitigation services and increase community resilience to climate change. Specifically, we find that the Otter Creek wetland–floodplain complex reduces downstream flood inundation costs by up to 92% across a range of flood intensities (Table 2). For Tropical Storm Irene alone, these wetlands and floodplains provided between $627,000 and $2,000,000 in avoided damages (Table 1). Beyond this one event, the expected annual value exceeds $126,000 and may be as high as $450,000. These values will likely increase under a changing climate, with extreme rain events already becoming more common. Our findings support the potential of wetlands and floodplains to act as green infrastructure that builds community resilience to climate change.

Our damage estimates represent only a fraction of the flood mitigation value provided. We focused on avoided damages caused by inundation of buildings in the town of Middlebury, omitting damages to infrastructure, profits lost to businesses, erosion damages (which often exceed those from inundation Vermont Agency of Natural Resources Department of Environmental Conservation Water Quality Division, 1999), insurance costs, agricultural losses, and less tangible impacts on human health. All of these factors may also be mitigated by upstream wetlands and floodplains.

The estimated mean annual value of $126,000 to $459,000 for this wetland complex is large enough to warrant explicit consideration of flood mitigation services in land use decisions. When we compare this value to rough estimates of the costs of wetland conservation, we find that flood mitigation benefits alone "payback" at least a quarter of the expense of conserving the Otter Creek wetland–floodplain complex (Table 3). This conclusion holds over a range of discount rates for our high scenario, and over all but the highest discount rates for the low scenario. High fixed discount rates are inappropriate both to human preferences over long time spans and to precautionary environmental decision making (Turner, 2007; Knetsch, 2005); thus, we find the lowest discount rates presented here are most applicable. Furthermore, this conclusion is conservative because we are likely to have overestimated conservation costs. Most of these wetlands are already protected under state and federal legislation (Vermont Agency of Natural Resources, 2012), and conservation is increasingly achieved through easements, which are more cost-effective than land acquisition (Merenlender et al., 2004).

That flood mitigation alone could pay back over a quarter of the costs of conservation is remarkable since conservation would also protect biodiversity and a number of other ecosystem services that provide quantifiable benefits to people, such as hunting, bird watching, recreation, and water filtration (Zedler and Kercher, 2005). A full analysis of the return on investment (ROI) in wetland conservation is beyond the scope of our study and would require more accurate estimates of acquisition and opportunity costs, as well as information on development risk. However, our rough comparison illustrates that ROI is likely to be generally positive, given that wetlands are under high risk globally (Zedler and Kercher, 2005).

While damage reductions were substantial in all ten historic cases, we found that the flood mitigation effects decreased for larger floods (Fig. 6). This result reinforces existing findings that wetlands are less important for larger, less frequent flood events (Interagency Floodplain Management Review Committee United States, 1994; Hundecha and Bárdossy, 2004). Beyond some threshold, the capacity of wetlands to absorb flood water may be overwhelmed, in which case no additional mitigation can be provided (Ennaanay et al., 2011). Green infrastructure solutions may therefore be best suited to address flood events with medium return intervals, whereas built infrastructure and careful development planning are more effective for the most extreme events.

Our findings support a growing body of literature indicating wetlands and floodplains can have large impacts on peak flows (Godschalk et al., 1998). Indeed, previous findings correspond more closely with our higher estimates of peak flows. For example, studies in New England using more advanced hydrological models have shown complete removal of wetlands can increase peak flows by over 200% (Ogawa and Male, 1986). Elsewhere, river channelization is estimated to increase peak flows by 50–150% (Acreman et al., 2003). Additionally, the discharge we estimated in Tropical Storm Irene under the no-wetland high scenario corresponds almost exactly to the 10-year flood discharge from a regional statistical model developed by the USGS when we remove the effect of wetlands (Olson and Veilleux, 2014, Table S1).

The economic value of flood mitigation services per area of wetland presented here is considerably lower than values obtained elsewhere via other methods. We estimated the value of the Otter Creek wetlands complex at less than $100 per hectare per year ($459,000 divided by

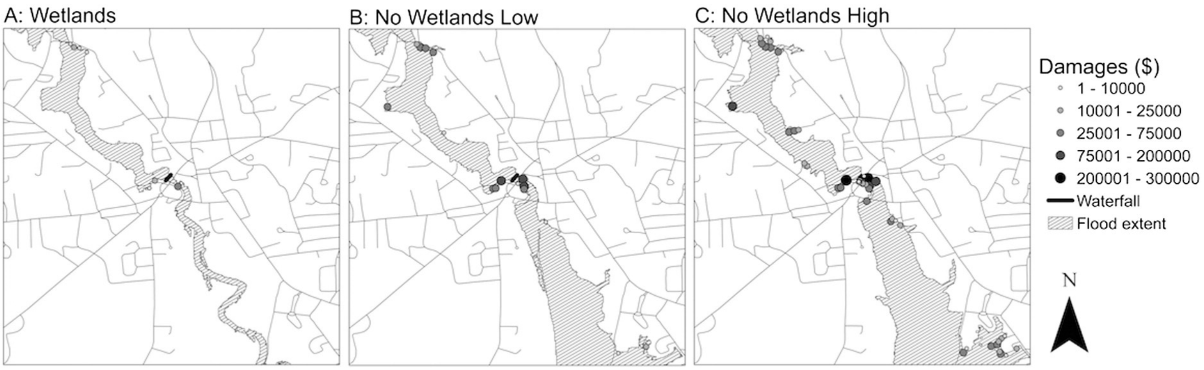

Fig. 5. Flood extent and damages to flooded structures in Middlebury following Tropical Storm Irene. Panel A: wetlands scenario. Panel B: no-wetlands low scenario. Panel C: no-wetlands high scenario.

Table 2
Value of wetlands and floodplains in terms of avoided flood damages for ten flood events in Middlebury, VT. Annual exceedance probability (AEP), damages with and without wetlands, and the resultant percent reduction and reduction in damages (value) for each flooding event are shown.

		Damages under each scenario			Value of wetlands and floodplains		Estimated damage reduction (%)	
Year	AEP	Wetlands	No-wetlands low	No-wetlands high	Low	High	Low	High
1976	1.02	$45,760	$204,962	$453,198	$159,202	$407,438	78%	90%
1947	0.44	$49,974	$130,429	$325,698	$80,455	$275,724	62%	85%
1956	0.42	$49,975	$161,232	$449,418	$111,258	$399,444	69%	89%
1984	0.25	$68,169	$157,101	$527,783	$88,932	$459,614	57%	87%
1948	0.14	$100,633	$243,401	$675,893	$142,769	$575,260	59%	85%
2011	0.14	$100,632	$498,760	$1,338,654	$398,128	$1,238,022	80%	92%**
1938	0.1	$127,032	$325,713	$1,043,294	$198,681	$916,262	61%	88%
1977	0.08	$152,857	$204,956	$439,190	$52,098	$286,333	25%	65%
1987	0.07	$157,088	$243,404	$457,925	$86,316	$300,837	35%	66%
1936	0.01	$338,114	$325,708	$523,519	−$12,405	$185,405	−4%	35%

** Tropical Storm Irene. The use of daily discharge data for historic flooding events underestimates flood damages; in the specific analysis of Tropical Storm Irene, we used 15-min discharge data and found a 95% reduction in flood damages.

7280 ha). Ming et al. (2007) have calculated the water storage capacity of wetlands in the Mogome National Reserve in China and value this storage function at $5700 per hectare per year using a replacement cost technique. Thibodeau and Ostro (1981) use an avoided damages approach to arrive at a similar value of $5000 per hectare per year. In the Economics of Ecosystems and Biodiversity (TEEB) database (Van der Ploeg and Groot, 2010), there is only one study related to water flows that does not transfer values from other studies; this study uses an avoided damages approach to calculate values of over $9000 per hectare per year (UK Environment Agency, 1999).

The quantity of ecosystem service depends on demand from human beneficiaries as well as biophysical supply (Fisher et al., 2009), and demand will vary widely depending on downstream population and infrastructure (Mitsch and Gosselink, 2000). Here we value benefits to a relatively small population of downstream beneficiaries, which may explain why the biophysical impacts we find are in line with other research efforts whereas our economic valuation is substantially lower than values found elsewhere. Although more sophisticated models exist to evaluate separately the hydrologic dynamics (Neitsch et al., 2011; Liang et al., 1994; Feldman, 2000) and economic damages (FEMA, 2003) of flooding, this dynamic stresses the importance of accounting for both biophysical supply and beneficiary demand.

We see three limitations to our approach. First, our no-wetlands scenarios rely on simplifying assumptions (Table S2) that result in a wide range of possible values. Future research is needed to reduce this uncertainty, to evaluate the effects of marginal (i.e., small) changes in wetland area, and to allocate value spatially within a watershed. Second, we extrapolate beyond the observed rating curve (Fig. 3) and assume this rating relationship applies throughout Middlebury. Many of the annual floods used to establish the rating relationship overtopped the main channel into the floodplain, which does not include a second topographic tier that we would expect to shift the rating relationship for any floods other than the most extreme cases modeled. In these most extreme cases, height may be slightly overestimated (Fig. S2). Because all floods inundated a wide floodplain throughout the study area, very large changes in volume would be required to cause noticeable differences in flood height, making our results less sensitive to this “bathtub” assumption. Further, our modeled flood extent are similar to flood extents from FEMA flood insurance rate maps despite this assumption (Fig. S3; Federal Emergency Management Agency: National Flood Insurance Program. p. Community Panel Number 500008 0003 A, 1985). Floods of historically unprecedented proportions resulting from

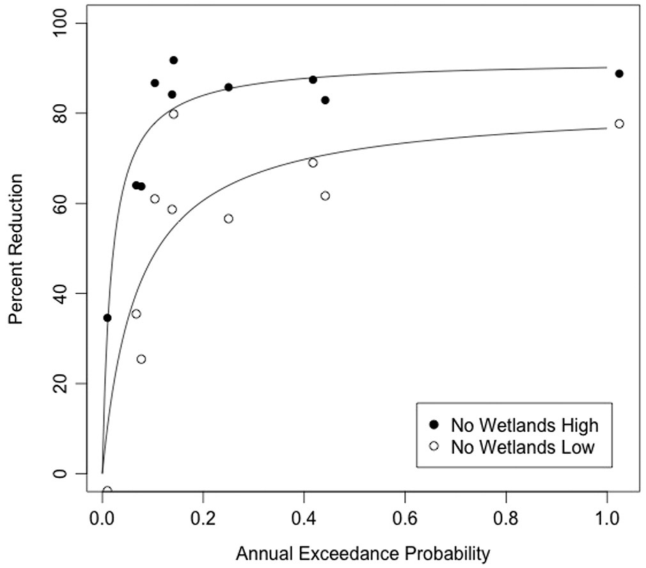

Fig. 6. The percentage reduction in damages resulting from flood mitigation services as a function of the annual exceedance probability of ten historic floods. Hollow black: No-wetlands low; solid black: No-wetlands high.

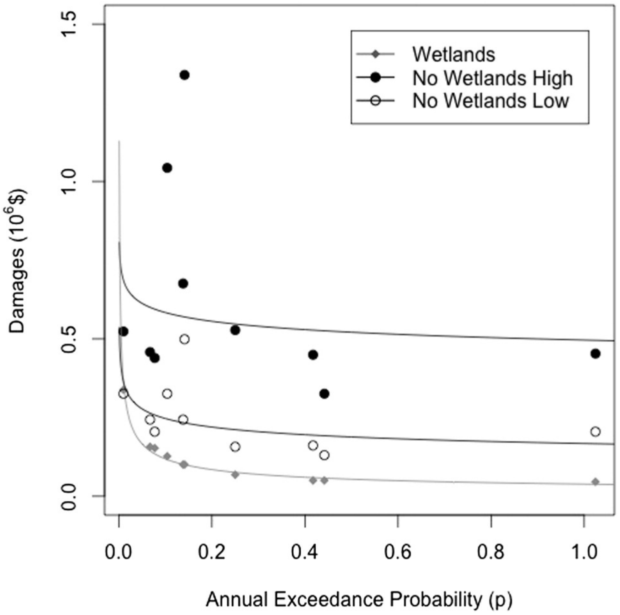

Fig. 7. Damage probability functions. Grey diamond: wetlands scenario (D = e^10.55757$p^{-0.48927}$, p = 4.367e−07, r^2 = 0.9646). Open black circles: no-wetlands low scenario (D = e^12.02817$p^{-0.16884}$, p = 0.1119, r^2 = 0.2851). Filled black circles: no-wetlands high scenario (D = e^13.11465$p^{-0.07055}$, p = 0.5626, r^2 = 0.04361).

Table 3
Value of flood mitigation services relative to conservation costs. Net present value (NPV) is calculated using a range of discount rates, and is compared against conservation costs as estimated by the cost of land acquisition. Ranges reflect low and high scenarios.

Source of discount rate	Discount rate	NPV (millions U.S.$)	NPV/cost of land acquisition
Mean agricultural land values and rents (National Agricultural Statistics Service, 2014)	0.9%	14–49.8	27–95%
Stern review (Stern and H.M.s. Treasury, 2006)	1.4%	9–32.8	17–62%
UK standard for cost–benefit analysis (Turner, 2007)	DDR*	4.4–16	8–30%
U.S. standard: water and related land use policy decisions (U.S. Bureau of Reclamation, 2014)	3.375%	3.7–13.6	7–26%
U.S. FEMA (FEMA, 2003)	4.125%	3–11.1	6–21%
U.S. Army Corps of Engineers (National Research Council, 2000)	7%	1.8–6.6	3–12%

* Declining discount rate defined by the UK Treasury for 100 years, then a 2.5% discount rate from 100 years onward.

land use and climate change will fall outside the observed rating curve, so preparation for these events necessitates extrapolation. Third, our damage functions are poorly fit to the data in the no-wetlands cases (Fig. 7). Variation in modeled flood peaks is to be expected given differences in temporal and spatial rainfall patterns, flood sizes, etc. While we cannot estimate the shape of the no-wetlands damage function with confidence, there is a consistent and significant vertical shift in the damage function as a result of wetland and floodplain loss (Fig. 7). This emphasizes the importance of natural landscapes for flood mitigation regardless of the functional form of the damage curve.

If the conservation of wetlands and floodplains provides large returns, why do wetland loss and river channelization continue? The value of wetlands is often considered to be negligible, even negative, in many decision-making contexts (Turner et al., 2000). Further, the costs of conservation and the benefits of avoided damages are realized by different groups. For instance, the costs of flood inundation are often spread among many downstream property owners and insurance agencies, whereas the opportunity costs of conserving wetlands must be borne by relatively few upstream landowners and municipalities.

Economic valuation can help clarify the impacts of land use decisions on people. Our findings provide evidence that preventing rivers from flooding surrounding wetlands and floodplains may only displace, and potentially increase, the total cost of flood damage (Wharton and Gilvear, 2007). Our most basic infrastructure, the ecosystems that support us, are in worldwide decline. In Vermont and nationwide, significant efforts are reconnecting rivers to their floodplains and conserving wetlands. This study illustrates that the benefits of these efforts are potentially quite large, and that the omission of ecosystem service outcomes from land use decisions may have real and severe consequences for people.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2016.05.015.

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