CHAPTER 5
Valuing land cover impact on storm peak mitigation

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5.1 Introduction
Images of floods displacing or even killing people provide a constant reminder of the power of nature and human vulnerability to natural disasters. Although storms and storm events are highly unpredictable, it is possible to use hydrological models to predict the magnitude of a particular flood, given information on the local geology, soil properties, vegetation, and management practices. We have developed approaches for quantifying the link between changes in land use and land cover (LULC), and flood risk. In flood management, risk has three ingredients: the hydrological response to a storm, the possible failure of flood protection infrastructure (such as a levee breaking), and the value of what might be destroyed by a flood. We focus on the hydrology and economic value of what may be destroyed, leaving structural integrity to be addressed by civil engineers. Given a well-defined storm, we estimate the severity of flooding in terms of water volumes and flow rates, and corresponding damages from the storm.

In general, the combination of meteorological (e.g., rainfall intensity, extent and duration of the event) and geophysical (e.g., basin size, basin geomorphology, soil characteristics, and land use) characteristics are the main factors influencing major flooding following large rainfall events (Hamilton and King 1983; Kattelmann 1987; Bruijnzeel 1990, 2004). In some situations, natural landscapes and vegetation can offer storm peak mitigation. For example, forests and deep permeable soils often reduce runoff as the result of enhanced soil infiltration and soil water storage capacity. Conversion of forests and wetlands to agricultural or developed land covers will tend to increase the volume of runoff and the flooding associated with storm events for medium and small return period events (Ennaanay 2006). However, forests have limited ability to mitigate flooding associated with large return period storm events because enhanced soil infiltration only captures a small fraction of total precipitation depth for such storms (FAO and CIFOR 2005). We develop models in this chapter that can help decision-makers take advantage of nature-based mitigation of floods and storm damage from medium and small return period events to avoid unnecessary flood risk due to poor land management.

This chapter presents two different types of models for quantifying the impact of LULC on storm outcomes. The data-sparse tier 1 model quantifies the reduction in storm peak volume due to LULC relative to bare soil on a parcel-by-parcel basis and values this reduction based on each parcel’s relative contribution to mitigation. In the present formulation the tier 1 model is not set up to predict the extent of downstream flooded area associated with a storm peak. The more robust, data-intensive tier 2 model provides probabilistic output for flood magnitudes as affected by incremental changes in the landscape mosaic and quantifies the incremental changes in risks associated with a specific flood volume, where risk is associated with a cost. In tier 2, the extent of flooded area is determined using the
Hydrologic Engineering Centers River Analysis System software (HEC-RAS) and streamflow time series from the Precipitation Runoff Modeling System (PRMS) model.

5.1.1 Storm peak mitigation modeling theory

For small to medium storms vegetation may retain water as it falls and flows through the landscape (through canopy interception, enhanced infiltration, soil water storage) and thus reduce peak flow. In a modeling study using the Hydrologic Simulation Program Fortran (HSPF) in the Cottonwood River watershed within the Minnesota River Basin, Ennaanay (2006) showed that conversion of different percent acreage (60, 75, and 86% of watershed area) of annual cropping systems (soy and corn) to perennial vegetation over a 50-year simulation period showed a decrease in annual instantaneous peak flows for small event storms, but not for larger event storms. Similarly, studies from small paired experimental basins showed that clear-cutting and road building increased only some peak storm discharges (Wright et al. 1990). Indeed, in the Pacific Northwest, increases in the peaks were greater for small early wet season storms but there was no significant increase in peak flows for the largest storms (Rothacher 1970).

Wetlands in both up- and downstream areas, and floodplains have a significant role in mitigating floods and storm peaks. Both land-use types have storage capacities higher than many other LULC types. Ennaanay (2006) showed that conversion of 27% of the annual cropping systems to wetlands could significantly reduce peak flows for small and moderate storm events. Wetlands not only reduce the peak flows but also significantly delay time to peak flows, and alter the inflow–discharge relationship and roughness. Floodplains have impacts similar to those of wetlands on flood mitigation and storm peak attenuation.

The spatial resolution of our models differs between tier 1 and tier 2. In tier 1, the analysis takes place at the parcel level, where parcel size is defined by the spatial resolution of the input data. In tier 2, the analysis is based on hydrologic response units (HRUs), which are homogeneous with regard to LULC, soil, and slope. It should be noted that while the LULC category is a key determinant of an area’s ability to intercept rainfall, the equations presented below will not include direct references to LULC categories, as they are captured by the parcel and HRU indices. It should also be noted that while the analyses in tiers 1 and 2 occur at the parcel and HRU level, respectively, the model results can be reported at other scales more relevant to management decisions such as individually owned parcels or counties.

The key parameters linking LULC to storm peak mitigation are canopy interception, soil infiltration, LULC type, soil water storage, and land-use positioning on the landscape. Peak flows will increase as soil infiltration, interception by canopy, or soil water storage is reduced. However, if the magnitude of storm depth becomes large, the impact that soil and plants have on storm flow peaks is small relative to water inputs (Bruijnzeel 1990; Brooks et al. 2003; Ennaanay 2006) and thus of reduced value in terms of flood risk reduction.

The impacts of land use on flooding also depend on the size of the area being examined. In particular, land-use impacts on flooding are most evident in watersheds less than 1000 km² (Kiersch 2001) because the sheer length of stream channels and extent of floodplains in larger basins provide storm peak mitigation, swamping the signal of land use. For example, forest harvesting has produced detectable changes in peak discharges in basins up to 600 km² in size. Increases are a result of changes in flow routing (due to roads) rather than to mere changes in water storage due to vegetation removal in small basins.

5.2. Tier 1 biophysical model

5.2.1 Modeling storm mitigation properties

The tier 1 model for storm peak mitigation focuses on a storm event of a specific size defined by the user. Our approach estimates the impact of land use on flood mitigation at the parcel level by determining the amount of on-parcel storm runoff retained by each parcel following a rainfall event. We use GIS capabilities to generate a synthetic hydrograph
for the defined size of storm (Martinez et al. 2002; Melesse et al. 2003) (Figure 5.1a). To do this, we estimate storm runoff volumes for each parcel given a LULC using the SCS–curve number (CN) method (Mockus 1972) and keep track of potential travel times from parcel to the watershed point of drainage. The synthetic hydrograph is formed by aggregating runoff of parcels with similar travel time class. Factors affecting travel time in the model include LULC surface roughness and slope. By identifying landscape units with equal travel times to the watershed outlet and summing the storm water that reaches the stream from these units, we create a hydrograph of a uniform storm depth, and associated duration. For model output to be useful for land managers, we generate a map of landscape contributions to these peak flows.

The tier 1 storm peak model runs for a single specified storm event and predicts the magnitude and the timing of the peak flow. The tier 1 storm peak is mainly based on the SCS-CN method, which is known to work well for the design of culverts and civil works storm flow infrastructure. Admittedly this is a very simple approach, but rainfall-runoff modeling always demands balancing model complexity versus available data. Interestingly, it has been found that more complex models are not necessarily more accurate than their simpler alternatives (Branson et al. 1962, 1981; Loague and Freeze 1985).

In order to evaluate the damage-mitigating properties of a landscape we apply the tier 1 model for storm peak mitigation for a known flood return period, and the expected damages of such a storm. Prior to applying the model in the watershed of interest, one must use regional rainfall data or rainfall-runoff models coupled to flood routing models to characterize the storm event $P_s$ related to flood event $s$ of probability $\pi_s$. This tier 1 model assumes that the storm rainfall depth is constant in time during the storm event and spatially uniform over the watershed of interest.

The tier 1 storm peak mitigation model calculates the direct runoff generated by each parcel on the landscape using the SCS-CN equations for the user-defined storm event (Kent 1972). The SCS-CN method is a simple, widely used, and efficient method for determining the approximate amount of direct runoff from a rainfall event within any particular parcel. We use this method to compute the rainfall excess as the remainder of precipitation after on-parcel infiltration loss. Direct runoff is generated by a wide variety of surface and subsurface flow processes, of which the most relevant ones are the Hortonian overland flow, saturation overland flow, shallow sub-surface flow, and through-flow (Ponce and Hawkins 1996). The Hortonian overland flow occurs when rainfall exceeds infiltration capacity. It is a characteristic of dry to semi-dry regions and areas where vegeta-

![Figure 5.1](image_url) (a) Storm hydrograph terminology and (b) synthetic storm hydrograph generated by the storm peak mitigation model.
tion is sparse and the soil surface is highly disturbed. The saturation overland flow occurs after the soil profile has become saturated because of either high antecedent soil moisture or high rainfall depth that fills in the soil profile; this mechanism is referred to as the Dunne mechanism. Shallow sub-surface flow describes the process that takes place when water flows downslope in the shallow soil profile quickly and contributes to storm flow. Kirkby and Chorley (1967) show that the shallow sub-surface flow can be similar to the through-flow that occurs in heavily vegetated landscapes with thick soil covers and less permeable soil profiles atop impermeable bedrock (Kirkby and Chorley 1967). In our approach we use the curve number to quantify runoff under the assumption that the storm event occurs uniformly throughout the watershed and that Hortonian runoff is the dominant process that generates the storm peak. Nonetheless, the CN method can be used in landscapes dominated by saturation overland flow as demonstrated by Boughton (1987), Steenhuis et al. (1995), and Lyon et al. (2004), but would require some adjustments in how we develop the synthetic hydrograph. Although initially designed for watershed catchment runoff estimates, a distributed CN method has been applied effectively to large parcels (from 900 m² up to several hectares) defined as HRUs in the Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998, and see Hawkins et al. 2009). There is no published guidance on an acceptable lower limit to parcel size for application of the CN approach.

The parcel size in our model is defined by the user and can be as small as is commensurate with input data. A common input data resolution is 900 m², corresponding with the resolution of widely available digital elevation models. Our approach of applying the CN model on a parcel-by-parcel basis that is then aggregated (distributed approach) rather than on a watershed catchment (lumped approach) is not standard. We argue that runoff differences between distributed and lumped approaches are minimized in evaluations of mid- to larger sized storm events since the curve number becomes more linear at greater volumes. In addition, since differences are smallest in homogeneous landscapes, such as natural landscapes, the user should be most wary of heterogeneous landscapes, such as heavily urbanizing encroachments into forests.

The SCS-CN equation determines storm direct runoff depth at parcel \( x \) for a flood event \( s \) that occurs with probability \( \pi_s \) generated by rainfall depth \( P_s \) as

\[
S_{xj} = \frac{25400}{CN_{xj}^*} - 254
\]

\[
Q_{xj} = \begin{cases} 
0 & \text{if } P_s \leq 0.2S_{xj}, \\
\left(\frac{P_s - 0.2S_{xj}}{P_s + 0.8S_{xj}}\right)^2 & \text{if } P_s > 0.2S_{xj}
\end{cases}
\]

where \( CN_{xj}^* \) is the medium soil moisture condition curve number adjusted for slope, 0.2 \( S_x \) is the initial abstraction, which accounts for the amount of precipitation occurring before runoff, or the rainfall interception by vegetation. The value has been set to 0.2 \( S_x \) through developmental history and documentation; however, Hawkins (1979) showed that using 0.2 \( S_x \) did not result in good runoff prediction unless \( S_x \) was dependent on rainfall amounts. \( Q_{xj} \) is the direct runoff or quick-flow that is potentially generated by \( P_s \) at \( x \).

The SCS-CN method uses the CN values that were developed and assumed to be appropriate for slopes of 5%. Our model uses the CN adjustment recommended by Williams (1995) to slopes different than 5%:

\[
CN_{xj} = \left(\frac{100-CN_{xj}}{3}\right) \times (1-2 \cdot e^{-13.86100 \cdot x_j^2}) + CN_{xj}
\]

where \( CN_{xj} \) is the CN value associated with LULC \( j \) in \( x \) applied for soil conditions of medium wetness type II (USDA 1986) with a 5% slope. However, the user can specify one of three wetness conditions (dry, medium, or wet): in temperate conditions, generally forested lands are drier than annual crops after long dry periods, and \( q_x \) is the parcel’s slope.

Once direct runoff is calculated, we estimate travel time of that water to the point of interest. When defining the drainage area to evaluate the storm-mitigating properties of the landscape, it is important to exclude parcels that drain into inter-
mediate flood control reservoirs. Thus, we define $X_p$ as the set of all parcels that flow into point of interest $D$ that are not routed through a flood control reservoir. The following equations provide a total time of travel for excess rainfall originating on a parcel in the landscape to a drainage point of interest, $D$,

$$v_i = \frac{1}{c_i} \sqrt{\theta_i}$$

$$T_{xy} = \sum_{y \in x, c \in y} \frac{y_c}{v_{xy}}$$  \hspace{1cm} (5.3)$$

where $x$ indexes parcels in the landscape; $v_i$ is an estimate for overland flow velocity; $\theta_i$ is the mean percent slope of parcel $x$; $c1/c_i$ is a roughness coefficient for each LULC type based on the National Engineering Handbook (Kent 1972; ASCE 1996) that relates slope and surface vegetation to velocities; $y_c$ is the distance travelled on parcel $x$ equal to the width of the parcel if flow direction is north, south, east, or west and equal to the hypotenuse of the parcel if flow direction is otherwise; and $T_{xy}$ represents the potential travel time that storm runoff from parcel $x$ is routed to point of interest $D$. There may be several drainage points of interest that might denote an area of high importance for flood mitigation. If so, the model can be applied iteratively for each point of interest.

Once travel times are calculated for each parcel, isochrones (sets of parcels with the same travel time class to the point of interest) are defined. Let us introduce $\tau_{xy}$ to represent isochrone $i$, where $\tau_{xy}$ is defined as follows for demand point $D$,

$$\tau_{xy} = \begin{cases} i = 1, \ldots, I & \\
\left[ (i-1) \frac{T_{xy} - D_{\min}}{I}, \frac{T_{xy} - D_{\max}}{I} \right] & \\
\end{cases}$$  \hspace{1cm} (5.4)$$

where $\tau_{xy}$ is a set of parcels $x$ with a similar class of travel time to point $D$; $D$ is the flood risk reduction demand point and is the reference for estimates of flow travel times; $i$ is an isochrone identifier; $I$ is the number of isochrones (time classes) in the analysis that is input by the user; and $T_{xy}$ is the maximum time of travel to the outlet. For example, Figure 5.1b depicts how the tier 1 storm peak mitigation model aggregates storm runoff of parcels within the same time class. In this example, most of the storm runoff generated by the storm event that reaches flood risk point $D$ arises from parcels in time class 3. In effect, our tier 1 model develops a lumped synthetic storm runoff hydrograph to identify the sources of storm peaks in the watershed.

The synthetic hydrograph allows the model to select parcels that contribute to mitigating the storm peak. The parcels, $x'$, most likely to contribute to mitigating the storm peak are those that lie between the peak and the demand point $D$.

The parcels $x'$ are found by determining the peak $Q_{cD}$ of the synthetic hydrograph. $Q_{cD}$, defined as aggregated runoff at each isochrones $i$, is defined as

$$x' \in \tau_{xy} \quad i = i^* \quad Q_{cD} \geq Q_{cD} \quad \forall i,$$

$$Q_{cD} = \sum_{x \in \tau_{xy}} Q_{xy}$$  \hspace{1cm} (5.5)$$

where, $i^*$ is the isochrone number that corresponds to the peak of the hydrograph and $Q_{cD}$ contains the highest volume of runoff among all isochrones. $Q_{cD}$ is the parcel runoff summed for each isochrone $i$. $x'$ are all the parcels that lie on the flow path between the point of demand $D$ and potential parcels that are likely in synchronicity with the storm peak.

### 5.2.2 Modeling the landscape benefits of storm peak mitigation

The service we want to represent on each parcel $x$ is the reduction in storm flow volume provided by vegetation. The tier 1 model does not account for infiltration or storage of storm flow reaching a given parcel $x$ from upslope. This means we give a conservative estimate of the minimum amount of storm peak flow mitigation provided by each parcel. The model calculates mitigated runoff by each parcel on the landscape and the contribution of each parcel to the storm peak at the point of interest.

The amount of storm peak mitigation associated with extant vegetation, here called direct mitigation, $DM_{cD}$, is determined by the runoff depth at each parcel $x$ retained by vegetation on that parcel,

$$DM_{cD} = \begin{cases} P - Q_{cD} & \text{when } x = x' \\
0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (5.6)$$
where $P_s$ is the storm depth and $Q_{sx}$ is the direct storm runoff at parcel $x$ for storm $s$, as defined in Eq. (5.1). It is important to note that as a storm event, $P_s$ gets higher such as in 50-year return period storms or greater, the amount of potential storm mitigation at $x$, $DM_{sx}$, tends to become smaller than the storm depth. In other words, large storms saturate the soil and make infiltration and storm peak mitigation negligible relative to the total storm depth. This is consistent with earlier assertions and observations that LULC properties to mitigate storm peak is reduced for larger storms.

We estimate the marginal storm runoff mitigation provided by land cover, $\Delta_{x,s}$, as a function of the marginal change in runoff with respect to total runoff for peak-contributing parcels,

$$\Delta_{x,s} = \begin{cases} \frac{DM_{sy} - DM'_{sy}}{\sum_{s \in x} (DM_{sy} - DM'_{sy})}; & x = x', \quad (5.7) \\ 0; & \text{otherwise} \end{cases}$$

where $\Delta_{x,s}$ is the parcel $x$’s contribution in the overall storm peak attenuation at the point of interest $D$ under storm $s$, and $DM_{sy}$ and $DM'_{sy}$ are the mitigation by parcel $x$ for the storm $s$ with the current LULC $j$ under the current scenario and a bare soil scenario, respectively. One can use Eq. (5.7) to map relative scores of storm peak mitigation as a means of identifying those watersheds with the highest priority for management. However, this method only counts flood mitigation by parcels that contribute to the peak flow. We do this because flooding damage occurs before and during the peak flood. Waters arriving after peak flood seldom cause additional damage. Given this timing–damage relationship, we do not want to assign social value to mitigation of flows that do not cause damage to humans. Again, this is a conservative estimate of the service provided.

### Example 1: Determining cell runoff, sources of the storm peak, and storm peak mitigation

For illustrative purposes, we model a watershed located in South-West Tanzania that flows into the town of Ifakara. The watershed has a drainage area of 32 km$^2$ with a diverse land cover. We applied the tier 1 model for a 30-year return period storm event of 150 mm. The results show areas where storm flow is being generated (Figure 5.2a). One can also identify separate travel time classes, and see which class contributes the most flow to the peak flood (Figure 5.2b). The darker zones contain parcels that contribute to the peak volume while the lighter are arriving either early or later to the watershed outlet, which is the point of interest. The tier 1 model generates output at the parcel level; however, a user can aggregate these outputs at larger scale to respond to specific needs (e.g., values could be aggregated to a map of individually owned parcels). Finally, we show the expected pattern of storm peak mitigation that occurred under this specific storm and this specific LULC scenario (Figure 5.3). These maps can help managers interested in stabilizing or improving natural flood control to identify two important parts of the landscape; (1) areas to protect because of their current high contribution to the reduction of storm peak flows, and (2) areas that currently contribute high flow to the storm peak itself. Managers may focus restoration or other improved management practices in the latter parts of the landscape to help reduce flood risk and damage (see also Box 5.1).

Since antecedent soil moisture is one crucial element that defines how much runoff is generated following a rainfall event, the user may need to modify the condition of expected antecedent soil moisture. As default we use medium antecedent soil moisture CN for given LULC. However, this can be adjusted upward or downward according to what is known about soil moisture conditions when the storms of interest arrive.

### 5.3 Tier 1 valuation

Storm peaks with longer return periods (i.e., lower probabilities of occurrence) are associated with larger expected areas of flooding. To mitigate the risk of flooding, society can (1) better manage the natural landscape to reduce the volume of water coming out of each parcel and to delay this water as much as possible so to spread the volume over a longer time period, (2) invest in man-made infrastructure such as levees and reservoirs to stop and store flood waters, and (3) manage people’s behav-
Figure 5.2  Storm volume upstream of the city of Ifakara, Tanzania. Areas with high CN, bare soil, and urban areas, presented by dark color, generate high volumes after the modeled storm event (a). Time classes of the storm hydrograph (b) show areas of the landscape that yield water that arrives in Ifakara during the storm peak flow (dark zones) or before or after the peak flow (light zones).
Runoff Mitigation (mm)

150

29.3

Ifakara

Figure 5.3  Storm peak flow mitigation map.
The land uses in this watershed have the capability to reduce and attenuate the storm volume from 29.3 to 150 mm for a storm event of 150 mm and antecedent moisture content (AMC) II.

Box 5.1 Integrated flood risk management: gaining ecosystem services and increasing revenue

David Harrison

It has become commonplace around the world to plan and construct dams for multiple purposes. If a dam is primarily conceived for hydroelectric generation, for example, it has seemed opportune to include other purposes, most commonly flood control. After all, if a large public works project is being built, it is only logical that it should provide as many benefits as possible. However, this simple proposition has serious downsides and has often led to perverse effects.

Flood control operations of a dam are achieved by lowering the reservoir water level during seasons of higher flood risk to maintain space to receive and hold flood waters for subsequent release at lower flow rates. The goal is to reduce the peak of the flood, or reduce the frequency of a flood of a given peak. Reducing the frequency of a flood may indeed produce calculable economic benefits. Water damage to property and disruption of economic activity is spread over more years and thus the annual cost is reduced. However, small increments of flood control can produce unintended consequences. For example, if the risk of a certain area of floodplain is reduced from a one in 10-year frequency to one in 40, the annual costs may be reduced by one-fourth. However, the exposure to serious human disaster—loss of life—is potentially increased as society relaxes vigilance with a false sense of security and neglects emergency preparedness.

Moreover, flood control imposed on a hydropower reservoir will generally cause substantial reduction of its revenue-generating potential. Full reservoirs produce more energy than reservoirs held partly empty, which is especially important in today’s energy situation. Making things worse, the trade-off of hydropower for flood control often occurs at inopportune times. In many monsoonal systems, the flood control season coincides with the high energy demand season. The time that reservoir levels are lowered in anticipation of monsoonal floods is the very time of highest energy demand in the system—the hot summer season with high demand for air conditioning and industrial cooling.

There is an alternative perspective in providing for multiple benefits from hydropower projects. Suppose the flood control reservoir function were shifted out of the reservoirs, thereby allowing increased energy generation.
ior in flood prone areas—i.e., flood plain management, through Federal Flood insurance in the USA—limiting development in flood prone areas is often the most feasible and economically viable option. None of these approaches is foolproof, and both have to be designed in reference to the particular severity of storm events. When severe storms occur, flooding is likely to ensue, particularly if the mitigation efforts are focused on less extreme events.

5.3.1 Calculating flood damage as a function of storm peak and LULC pattern

Our models are not designed to predict the flooded area. This means that if one wants to calculate damages they need to obtain flooded area maps. In the USA, flood footprint maps can be obtained from Federal Emergency Management Agency (FEMA) or flood insurance companies. In the developing world local knowledge (Tran et al. 2009) can help piece together scant information. It may often be necessary to develop flood prints directly using river channel hydraulic software such as HEC-RAS (USACE, 2002; ESRI-HEC 2004) applied to each storm of interest. Once floodmaps have been obtained, using economic valuation techniques, we attach a damage value to each of the mapped flood events. To isolate the value of storm peak mitigation provided by LULC, we must compare the damages associated with events on bare soil with events on extant vegetation.

3. Use funds for regular assessment of the condition of flood plain infrastructure—inspection and maintenance of those levees and detention facilities—to reduce risk of infrastructure failure.

4. Develop new financial instruments for flood risk coverage. Reinvent flood insurance applications to be based on incremental hydropower revenues. Recognize that inevitably water will occupy the land at some times, but that productive uses of the land will otherwise continue.

The fundamental idea is that integrated planning for flood risk management, hydropower production, and ecosystem protection has much to offer over simply imposing multiple purposes on planned infrastructure.

5.3.2 Determining $D_{ks}$

Flooding can affect crops, infrastructure, and the production of valuable ecosystem services. Under certain conditions, the magnitude of flood events is impacted by the pattern of land use in a watershed. The value of storm peak mitigation increases with the ability of a LULC scheme to reduce the peak flow after a significant rainfall event in the watershed.

In this model, we determine each parcel’s contribution to a flooding event at the watershed’s base. Next, we identify each parcel’s contribution to the economic damages in the flood area. Finally, we determine the potential savings or additional losses in total flood damage when a parcel changes LULC.

Let $V_{xt}$ indicate the total economic value of parcel $x$ in year $t$. If possible, $V_{xt}$ should include all market values and monetized ecosystem service values. The total present value of damage due to a flood in area $k$ with storm peak $s$ is given by

$$D_{ks} = \sum_{x \in k} \frac{\alpha_x V_{xt}}{(1+r)^{-t}} + \frac{C_{sT+1}}{(1+r)^{T+1}},$$

(5.8)

where $x \in k$s indicates the parcels in $k$ that are flooded given storm peak $s$. $T$ indicates the number of years for which the value of parcel $x$ cannot be fully realized due to storm peak $s$. $\alpha_x$ is an approximation of $x$’s portion of the value damaged by the flood in each year (i.e., if a flood covers land upon which a
20-story skyscraper is built, the entire value of that building may not be lost as a result of the storm event, although the ability of workers to go to their office might be). $C$ represents the costs that must be incurred in order to return parcel $x$ to its productive capacity (e.g., construction costs to rebuild structures). $r$ represents the annual discount rate. While the linear damage function (area-discharge) might seem arbitrary, Dutta et al. (2003) specify depth–damage curves for urban damage estimation that are linear until 3 m of depth above the floor level, the depth at which the damage function plateaus at 60% of total structure value.

As noted in Merz et al. (2004), the majority of flood damage estimation methodologies are based on direct tangible damage caused to structures in the flood zone. However, the cost of inundating land may be greater than the structural damage caused by the storm event. The true costs imposed by the flooding are the stream of profit and service values foregone during the period of inundation and drainage as well as any expenses that must be incurred to return the parcel to productive use.

Information on the stream of expected profit and service values at the parcel level may be difficult to gather. In many cases, especially if the flood event in question affects urban or rural-residential areas, the value of real estate can proxy for the discounted stream of all future profits emanating from a parcel (Polasky et al. 2008). Note that such an approximation is only reasonable in areas with fully functioning land markets. Because the value of real estate in functioning markets reflects the infinite profit stream associated with optimal use of a parcel, but a parcel will only be impaired for a period of time ($t$ to $T$), $V_{xt}$ could be set equal to

$$V_{xt} = \sum_{t=1}^{T} \frac{RV_t}{(1+r)^{t-1}}$$

where $RV_t$ is the annual rental value of real estate in parcel $x$ in year $t$.

The value of storm peak mitigation is captured by the difference in expected damages due to the presence of vegetation in the landscape. In the tier 1 model, the area of the landscape inundated by storm $s$ is not impacted by the LULC pattern. As a result, we are unable to identify how the presence of native vegetation mitigates the damages caused by flooding. We provide an estimate of the true value of this impact as

$$B_{xs} = D_{vs}(1-\omega_{vs}/\omega_{bs}),$$

where $\omega_{vs}$ represents the volume of post-peak water delivered to the damage point during storm $s$ when the landscape is covered by the current LULC pattern and $\omega_{bs}$ represents the volume of post-peak water delivered to the damage point when the landscape is covered by bare soil.

The model then aggregates sources of runoff from parcels into isochrones. Finally, we distribute $B_{ks}$ across the parcels that are in isochrones that precede the peak. These groups include all parcels that contribute water to the storm flow that impacts area $k$. $B_{ks}$ is distributed among these parcels according to each parcel’s relative contribution of water volume. Let $B_{ks}$ represent parcel $x$’s share of $B_{ks}$, where $B_{ks} = \sum_{x \in X} B_{ks}$, $x$ indexes the parcels contributing to the storm volume, and $X_{ks}$ is the set of all such parcels. Then $B_{ks}$ can be defined as

$$B_{ks} = B_{ks} \cdot \Delta_{\omega \leq \omega_{bs}}$$

where $D_{ks} = 0$ if $x$ lies within a time class that precedes the storm peak, or the storm return period is greater than 100 years, assuming that at 100 years, LULC has no significant impact on reducing storm peak.

### 5.3.4 Accounting for the distribution of storm peak return periods

Whether or not a particular return period storm will occur on a landscape in any given year (i.e., the probability that a particular storm peak will occur on the landscape in any given year) is uncertain. The return period indicates on average whether a flood of a particular size will occur at least once during that time period.

Accurate valuation of storm peak mitigation requires calculation of the expected damages
avoided due to extant vegetation. To calculate expected damages, the user must determine the damages associated with several different return periods. To determine damages and flooding extent for each it may be necessary to run a flood routing model, such as HEC-RAS, for different storm events because flood hazard maps are often tied to a few specific probability events—often targeting the longer return periods (50–100) not affected considerably by land use.

Let \( \pi_{ks} \) indicate the probability that a storm that will produce storm peak \( s \) at \( k \) will occur on the landscape in any given year. Then,

\[
D_k = E[D_{ks}] = \sum_{s} \pi_{ks} D_{ks},
\]

where \( D_{ks} = 0 \) for any \( s \) that has a return period of 100 years or more. In order to identify the expected value of storm peak mitigation by vegetative cover on parcel \( x \), we can modify Eq. (5.12) above to develop the expected value of mitigation on cell \( x \) with LULC \( j \) as

\[
B_{di} = E[B_{ki}] = D_k \times \Delta_{\pi,Di}.
\]

**Example 2: Economic valuation of the landscape for its storm peak mitigation**

In our example catchment in Tanzania (Figure 5.4), we applied the tier 1 storm peak mitigation model for the watershed flowing into the city of Ifakara for a 150-mm storm depth and hypothetical US$100,000,000.00 flood damage. Damage values are distributed on the upstream parcels that have travel time within the time classes that are less than or equal to time to peak. The assignment of value is proportional to the amount of storm peak reduction caused by the parcel’s vegetation, relative to bare, saturated soil. The value of a parcel is a function of its capability to reduce the excess-rain volume since the travel time is mainly a function of the distance to the outlet, slope, and a small impact of the parcel roughness associated with the land-use type. This map shows values ranging from US$0 to US$1022 per hectare, representing the wide range of flood mitigation provided by the wide range of land-use categories present in this watershed. However, these results do not reflect the full natural system characteristics such as storm depth variability within the watershed, and the storage capacity of different land-use categories.

![Landscape Value ($)](image)

**Figure 5.4** Economic valuation of the landscape for avoided flood damages.
5.4 Tier 2 supply and use model

5.4.1 Peak flow model and flood analysis

We are in the process of developing a tier 2 storm peak flow mitigation model, which will be based on assessing incremental changes in risk given changes in land use. This model under development combines several components of existing models in order to bring attention to the role of extant vegetation in regulating storm peak flows. The tier 2 approach will use PRMS (Leavesley et al. 1983) or a similar model to evaluate specific characteristics of landscape vegetation in mitigating storm peaks. Currently, the CN approach lumps all known LULC infiltration and storage functions into one number. In contrast, our tier 2 approach is being designed to independently evaluate canopy interception, rooting effects, soil litter, and many other functions attributed to mitigating runoff. Moreover, the model will incorporate hydraulic routing impacts on mitigating storm peaks, such that the user is informed about the relative impact of vegetation versus landscape geomorphology and scale.

As in tier 1, the tier 2 model will generate maps of a parcel’s contribution to each peak flow of interest and the parcel’s mitigation of the storm that caused that peak. Specifically, we will assess the incremental changes in risk given a change in landscape or climate using the flood frequency analysis methods by running different LULC scenarios with incremental storm intensities (Figure 5.5). This figure is known as the flood frequency analysis curve. We

![Figure 5.5](image-url)  

*Figure 5.5*  Flood frequency analysis for several scenarios of land use and climate.
will develop such curves using the simulated or observed annual peak flows in a statistical method, such as that used in USGS-PeakFQ (Flynn et al. 2006) software, to construct frequency distributions for different recurrence intervals. Different land-use scenarios and/or different climate scenarios will be used to generate different annual peak time series that reveal the impacts of land-use changes and climate changes on the peak flow and extent of flooded area.

Using the annual peak time series generated above, one can run flood frequency analyses to determine the peak flow associated with each return period. Then, for each return period, HEC-RAS can be used to generate flooded area profiles at river cross sections of interest. Valuation will require the input of an area-value index map that, when overlaid with the surface area profiles maps, will allow estimation of approximate damages in the flooded area around the stream (Figure 5.6).

Area-value index maps usually focus on damages associated with loss of property and infrastructure. We will provide the additional capacity in our tier 2 model to estimate agricultural crop damage from drowning or soil saturation. The modular flow estimation component of tier 2 will include a module that tracks the soil moisture in every HRU. The module will contain a component to define the duration of soil moisture greater than the field capacity and create a time series identifying the duration of excess moisture conditions. This information will be coupled with the tier 2 agricultural production model’s information on crop growth stage and crop flood to estimate the agricultural crop damage occurring after storm events.

5.5 Tier 2 valuation

The economic valuation for tier 2 will be similar to that in tier 1, except that increased spatial and temporal resolution will allow for the extent of flooding to vary across LULC scenarios. Given this enhanced realism, we replace our proxy for the value of native vegetation on the landscape as described in Eq. (5.12) above, with the true value,

$$B_{s2a} = D_{s2a} - D_{s1o}$$

(5.14)
where $D_{kbs}$ represents the damages when the landscape is covered by bare soil, and $D_{kfs}$ represents the damages with the current LULC pattern.

### 5.6 Limitations and next steps

The tier 1 storm peak mitigation model uses the CN model to only evaluate landscape parcels for their potential to store water from precipitation and keep it from becoming direct runoff. Runoff from snowmelt, ice, sleet, or rain on frozen ground is not estimated with this model because under these conditions vegetation plays a negligible role in mitigating storm peaks. Our current tier 1 approach also does not value the benefits from vegetation to extend flow routing times (i.e., expand the base of the synthetic hydrograph resulting in lower storm peak). This can be resolved in the next steps. Additionally, our model does not include the in-stream channel and floodplain attenuation due to friction and expansion–contraction energy losses in routing. This means that floodplain management, which is one of the most effective strategies for reducing damages associated with storm peaks, is not accounted for by our tier 1 model (it is addressable with a tier 2 model). When running a tier 1 analysis that does not include the value of floodplains, one is assessing a complementary strategy to floodplain management or restoration—a strategy that places value on the benefits that a forested landscape might have to mitigate storm peaks.

The main limitation of our approach is that we are applying a tool created for lumped watershed analysis at the parcel scale. Curve numbers are dependent on land cover, hydrologic position, soil type, and moisture content, each of which vary considerably spatially. In most models, an area-weighted average CN approach is used to assign a single value for a region or for a small subgrouping of areas considered homogenous (SWAT, HEC-1). Recently, however, work has been completed to assess whether improvements can be attained from using a more distributed CN approach. In comparing the effects of composite versus distributed CNs on estimates of storm runoff depths, Grove *et al.* (1998) showed that distributed CNs provide closer estimates particularly for wide CN ranges, low CN values, and low precipitation depths. However, the authors noted that for larger design storms (> 50- to 100-year return period) the difference in the runoff computed using composite and distributed CNs is minimal.

There is no explicit provision for the appropriate spatial extent at which to apply the CN approach. By design the method is assumed to apply to small and mid-sized catchments (Ponce and Hawkins 1996). Simanton *et al.* (1973, 1996) found that CN varied inversely with drainage area and noted a CN decrease of 2.2 units/100 ha of drainage area reflecting the substantial role of transmission losses. White (1986) showed the CN approach effectively predicted stream flow for a large (421 km²) watershed in eastern Pennsylvania. Several studies have also shown that rainfall heterogeneity within larger watersheds is an issue when applying the CN method (Van Mullem *et al.* 2002). Our model requires one uniform storm depth where in reality storms can hit watersheds with different rainfall depths. Furthermore, with the CN approach rainfall intensity and duration are not considered, only total storm depth. However, Hawkins (1975) noted that for a considerable range of precipitation values, accurate CNs are more important than accurate rainfall estimates.

Given these limitations, one should not use outcomes from these tier 1 models to argue for the replacement of a flood reservoir. However, they can be used to value portions of the landscape that are often neglected and that contribute to flood mitigation. We will continue to develop these models, and are working to incorporate a new approach where the CN is used to compute runoff from variably saturated source areas (i.e., saturation overland flow process of runoff generation). This new approach began with Boughton (1987) and has been followed by Steenhuis *et al.* (1995), Lyon *et al.* (2004), and Nachabe (2006). The latter studies have shown that by incorporating surface topographic characteristics into quantifying CNs for an area the accuracy of runoff prediction improves significantly. Further development of this new approach should improve the accuracy of the CN method for prediction of runoff from agricultural, forested, and range-land areas.

We are also exploring the addition of a method for including infiltration of runoff from upslope
parcels. This would provide a more full accounting of the role parcels play in drawing down flood peak flows and give a more realistic (rather than conservative) estimate of the storm flow peak mitigation benefits provided by vegetation and soils.

Lastly, it should be noted that although flooding has many adverse impacts, some beneficial impacts do exist. Flood waters inundate floodplains, leaving the soil moisture content and soil fertility high, which can prove beneficial for agriculture, depending on the crop cycle (World Bank 1990). In many parts of the world, floodwaters replenish groundwater aquifers, allowing them to fully recover. These represent additional ecosystem services that will need to be represented with other models. It may be important to consider these positive features of floods when comparing the cost-effectiveness of nature-based as opposed to concrete-based approaches to mitigating flood risk.

References


