# Post-Impact Analysis of Disaster Relief Resource Pre-Positioning After the 2013 Colorado Floods

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## ABSTRACT

Pre-positioning of supplies is important to facilitate disaster relief operations, however it is only after a disaster event occurs that the effectiveness of the pre-positioning strategy can be properly assessed. With this in mind, this paper analyzes a risk-based pre-positioning algorithm, developed for the American Red Cross, in the context of its actual performance in the 2013 Colorado Front Range floods. The paper assesses the relative effectiveness of the pre-positioning approach with respect to historical asset placements, and it discusses changes to the model that are necessary to support such comparisons and allow for further model extensions.

### Keywords

Disaster Operations Management, Facility Location, Humanitarian Operations.

## INTRODUCTION

The Rocky Mountains in the United States are susceptible to a number of different types of natural hazards over the course of any given year, including winter storms, landslides, wildfires, and flooding. Given the likelihood that the population will be impacted by one or more of these events, the American Red Cross in the states of Colorado and Wyoming has the responsibility to pre-position containers of supplies around the state, in order to be prepared for opening disaster shelters when they are needed. These supplies are either stored in trailers that can be easily moved to new locations, or in caches that are semi-permanently located in facilities such as community centers or firehouses.

The Red Cross has traditionally determined how to allocate the limited number of trailers and caches available in the region by effectively just maintaining supplies in the same locations in which they had always been placed. Because this does not necessarily provide the best coverage for the evolving population, however, they undertook an initiative to build an analytical model that could optimize the positioning of the supplies, as described in Arnette and Zobel (2019). The risk-based model that resulted from this project provides a more effective, and equitable, approach for pre-positioning such resources under uncertainty.

The following discussion specifically assesses this risk-based analytical model with respect to its ability to actually support opening disaster relief shelters during the 2013 floods along the Front Range in Colorado. We begin with a brief overview of the literature and of the pre-positioning approach and then perform a comparative performance analysis using actual data from the flooding event. This preliminary analysis serves as a validation of the effectiveness of the approach, but it also helps to identify opportunities for further research into improving the operational effectiveness of disaster shelter management.

## LITERATURE OVERVIEW

Determining proper locations for distribution facilities, as well as stocking levels for the resources stored at these facilities, is critical for avoiding delays in the immediate response to a disaster. Consequently, there are a number of existing research efforts in the literature that focus on facility location and stock pre-positioning for different types of humanitarian relief operations (Jia et al., 2007; Balcik and Beamon, 2008; Rawls and Turnquist, 2010; Duran et al., 2011; Caunhye et al., 2012; Arnette and Zobel, 2019).

Within this body of literature, only a few studies explicitly incorporate the concept of risk into their analysis. Campbell & Jones (2011), for example, discuss risk in terms of the probability that a facility will be destroyed or become inaccessible due to the disaster event. Akgün et al. (2015) also model the risk of a disruption to each facility, but they extend the notion of risk to three distinct components: threat, vulnerability, and consequence. Arnette and Zobel (2019) adopt a similar conceptualization of risk that consists of the three measures of hazard likelihood, exposure, and vulnerability, but they focus instead on the risk to the affected population due to the hazard event.

Such explicit consideration of vulnerability, and of the equitable distribution of resources to vulnerable populations, is extremely important for improving the effectiveness of humanitarian operations management (Sherali et al., 2004; Van Wassenhove & Pedraza Martinez, 2012). Holguín-Veras et al. (2013) discuss the need for developing objective functions for humanitarian logistics models which include a valuation of the effect of denying humans access to a necessary service. The modeling approach that we expand upon below provides a good example of this.

## PRE-POSITIONING MODEL

The pre-positioning model of Arnette and Zobel (2019) combines the likelihoods of the different hazards, the exposure of the population to those hazards, and the social vulnerability of that population, to create a county-level measure of the risk that individuals will not have access to an appropriately stocked shelter when they need it. This risk can be offset by positioning either trailers or caches in each county, so that the resources are available to open usable shelters. As discussed in Arnette and Zobel (2019), the model then minimizes the residual risk associated with not addressing the needs of the entire exposed population in each given county:

$$R_i^r = (\sum_{j=1}^{n} H_{ij} E_{ji}^r))V_i \tag{1}$$

where *r* indicates residual risk, $H_{ij}$ is the likelihood that hazard $j$ (out of *n* possible hazards) will occur in county $i$, and $V_i$ is the social vulnerability for that county.

$$E_{ij}^r = f(E_{ij}) - (W_T T_i + W_C C_i + W_{AT} AT_i) \tag{2}$$

is then the amount by which the exposure to hazard $j$ in county $i$ is reduced by allocating $T_i$ trailers and $C_i$ caches to that county, together with the $AT_i$ additional trailers that are available to be moved from adjoining counties. The exposure function *f()* in equation (2) captures the nonlinear relationship between the exposed population, $E_{ij}$, and the number of shelters needed, and the weights ($W_T, W_C, W_{AT}$) represent the relative value of the different resource types (Arnette and Zobel, 2019).

When this model is applied to the set of counties that make up the states of Colorado and Wyoming, using the appropriate data for hazards, exposure, and vulnerability, an optimal allocation for both trailers and caches can be generated for the entire region. Figure 1 shows the results of this, where the map to the left represents the county-by-county risk levels associated with the current allocation of resources and the map to the right represents the corresponding risk levels associated with the new, optimal allocation. Overall, the pre-positioning model helps to improve the risk reduction dramatically, from 60.04% in the original case to 81.13% in the optimal case (Arnette and Zobel, 2019).

Despite the significance of this improvement, however, it is important to keep in mind that these results only reflect the potential benefit associated with pre-positioning the available resources at the beginning of the year, in advance of the range of natural disasters that might occur across that region in the future. To help validate the approach, it is also important to look at the effectiveness of the allocation once an actual disaster event occurs. The following discussion does this in the context of the 2013 Colorado floods.

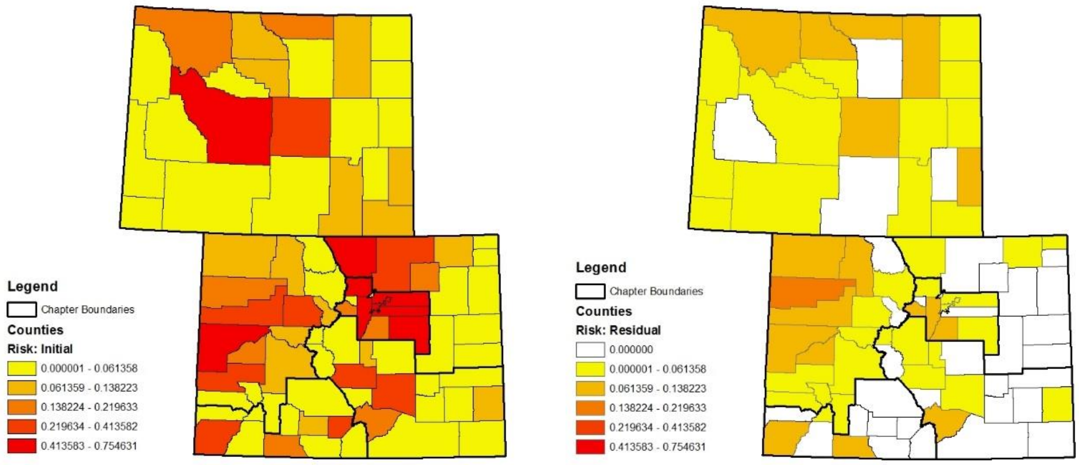


**Figure 1. Average risk reduction for original allocation (left) and optimal allocation (right) (Arnette and Zobel, 2019)**

## ASSESSMENT AND ANALYSIS

Stretching from the Wyoming border in the north to Pueblo in the south, the Front Range corridor of Colorado is the most densely-populated region of Colorado, including Denver, Colorado Springs, Boulder, Fort Collins, Greeley, and the surrounding metropolitan areas, for a total population of more than 4.4 million (United States Census Bureau, 2012). On September 10th, 2013, rain began falling on much of the Front Range, intensifying on the 11th and 12th before finally receding by the 15th. During this period double-digit inches of rainfall were reported in most of the Front Range, with the city of Boulder recording more than 21 inches (Coffman, 2013).

During the most intense periods of flooding that followed, over 12,000 people were evacuated and at least 1,000 people were isolated in Larimer County alone (Coffman, 2013). Approximately 4,500 square miles, or 2.88 million acres, were impacted by the flooding (Dreier & Neary, 2013). On September 12th, President Barack Obama signed an emergency declaration for Boulder, El Paso, and Larimer counties (Federal Emergency Management Agency, 2013a), with an additional twelve counties added to the emergency declaration on September 15th (Federal Emergency Management Agency, 2013b). The flooding caused hundreds of road closures, particularly in the northern portion of the Front Range. This led to several towns being isolated, as well as limiting access to many other towns in the region and generally making travel more difficult for residents needing to evacuate and organizations looking to provide assistance.

The Red Cross was the lead sheltering organization in the region, with a total of 30 shelters opened during the period from September 12th to September 29th and 5,659 shelter occupant nights provided. The maximum number of shelters open at the same time was 14, with a maximum of 999 shelter occupants in a single night. Many shelters were open only for a night or two, while the longest any shelter remained open during this period was 17 nights. A summary of shelter information by county is presented in Table 1 below. The numbers of shelters is the total number that were open and operating during the time frame mentioned above, while the “Max Pop” value is the maximum number of people in shelters in that county on a single night. Both Denver and Jefferson county, located immediately to the west of Denver, each opened a shelter, but had only single-digit occupancy and closed after one evening; but Adams county, immediately to the east of Denver, was also open for a single night but had over one hundred shelter residents. However, flooding in the immediate Denver area was minimal compared to counties located in other areas of the state. The three counties hardest hit by flooding, and thus sheltering needs, are located north of Denver: Boulder, Larimer, and Weld. While not far from Denver, Boulder county had the greatest sheltering needs, with twelve shelters being opened for a total of 52 nights of sheltering, and 2,633 resident/shelter nights. The maximum time a shelter in Boulder was open was for twelve nights. North of Boulder, and bordering Wyoming, is Larimer county, which opened four shelters for a total of 39 nights, and 930 resident/shelter nights. To the east of Larimer is Weld county, which had six shelters for a total 29 nights and 1,524 resident/shelter nights.

The actual asset placements for both trailers and caches at the time of the flood (i.e., the original allocation of resources, as illustrated for the entire region in Figure 1) are shown in Figure 2, along with the maximum population values for each of the shelters that was opened in response. Our preliminary analysis focuses just on the trailers. The table above also contains information regarding this original allocation.

The "Coverage" value in Table 1 reflects the percentage of the in-county shelter population that could be covered by assets that were available within that county at the time of the flood to facilitate sheltering openings and ensure enough cots, blankets, and other essential materials for shelter residents. Across these counties, 77.61% of need could be met by the 22 caches and 5 trailers that were available, and these resources were actually utilized within the counties. In Table 1, if the number for a given county is less than 100% then additional assets beyond those provided by the pre-positioning allocation were needed to facilitate shelter openings within that county. This means some of the sheltering needs were not met with readily available supplies in Adams, Weld, and especially Boulder, which had only 18.12% of sheltering needs met by supplies available within the county. The corresponding number of people that were not covered by the in-county assets was then used to calculate the number of additional trailers needed from other counties.

**Table 1. Trailer allocations by county, related to actual shelters for flooding event**

| | | | Original Allocation | | | Model Allocation | | |
|---|---|---|---|---|---|---|---|---|
| County | # of Shelters | Max Pop | Coverage | Trailers Needed | Trailers Allocated | Coverage | Trailers Needed | Trailers Allocated |
| Adams | 1 | 111 | 67.57% | 1 | 1 | 225.23% | 0 | 0 |
| Arapahoe | 1 | 18 | 277.78% | 0 | 0 | 1805.56% | 0 | 0 |
| Boulder | 12 | 552 | 18.12% | 7 | 3 | 58.88% | 4 | 4 |
| Denver | 1 | 6 | 2083.33% | 0 | 0 | 6250.00% | 0 | 0 |
| El Paso | 1 | 70 | 714.29% | 0 | 0 | 750.00% | 0 | 0 |
| Grand | 1 | 163 | 107.36% | 0 | 0 | 46.01% | 2 | 2 |
| Jefferson | 1 | 1 | 10000.00% | 0 | 0 | 30000.00% | 0 | 0 |
| Larimer | 4 | 190 | 184.21% | 0 | 0 | 171.05% | 0 | 0 |
| Logan | 1 | 19 | 526.32% | 0 | 0 | 263.16% | 0 | 0 |
| Morgan | 1 | 31 | 241.94% | 0 | 0 | 241.94% | 0 | 0 |
| Weld | 6 | 228 | 54.82% | 2 | 1 | 98.68% | 1 | 1 |

In the original pre-positioning optimization, trailers from adjacent counties were given partial weight in each county that directly bordered their actual location. We assume, however, that a trailer can only be reallocated once, and therefore available trailers are only allowed to count once overall. We then looked at how many trailers were available in adjacent counties, and found that one trailer could be moved to Adams, satisfying all of the need there. Even though the shelter in Adams was only open for one night, there were insufficient supplies available on the single trailer that was available in the county, thus an additional trailer was needed. However, because there are adjacencies in common between the three counties with need for additional trailers, this removed one available trailer that could also have been moved into Boulder. Ultimately, no matter how the trailers were allocated, there was need for ten additional trailers at the time of the flooding, but only five were available to be allocated to those three counties, leaving 50% of the additional need unable to be covered by trailers available in close proximity. Under the original allocation above, Boulder and Weld remained in need of additional trailers, and moving from adjacent counties to secondary-adjacent counties, there were still not enough trailers available to meet the full needs of these two counties. This reflects the reality of what transpired at the time of the floods, when trailers from Wyoming were being moved into Colorado to meet the additional needs for sheltering supplies.

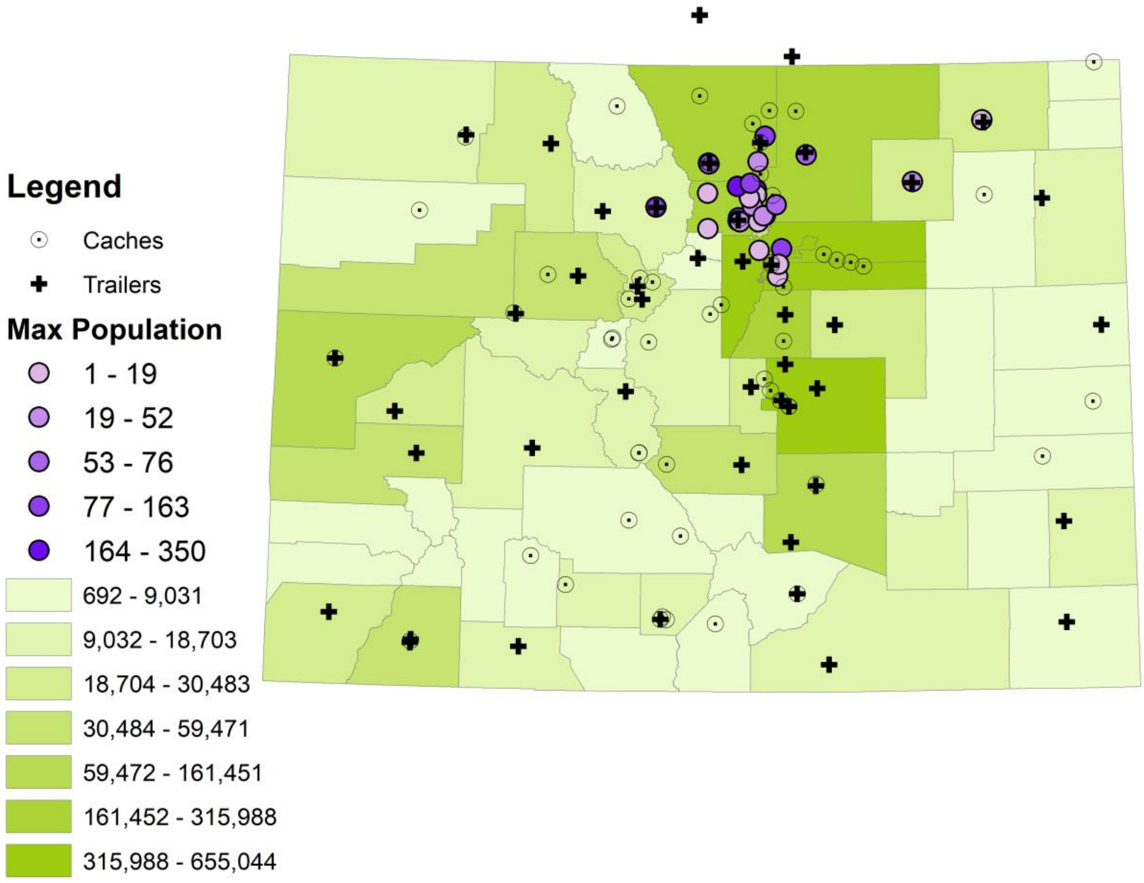


**Figure 2. Original asset placements and population levels by county at time of floods in 2013**

Figure 3 subsequently shows the locations of the trailers that resulted from the optimization model. Exact locations for trailers were not determined by the model because the Red Cross only wanted to know which counties should be allocated assets. However, there is a correlation between the number of trailers provided and the population centers, reflecting the greater need for sheltering supplies in areas with greater risk, of which population exposure is a component. Returning to Table 1, the last three columns represent values associated with this optimized allocation, including the new values of "Coverage." While two of the three counties that were originally unable to meet all sheltering needs are still unable to do so with the new allocations, one county (Adams) is fully covered by the new allocation, but one county covered under the original allocation now has uncovered need (Grand). However, 88.16% of total need across the eleven counties was met using all 10 caches and only 15 of the available trailers. Additionally, the smallest coverage value increased from 18.12% to 46.01% with the new model allocation. The total number of trailers still needed was reduced from ten to seven in the new allocation, and all seven could be provided from adjacent counties, with a few unused trailers still remaining within the immediate area.

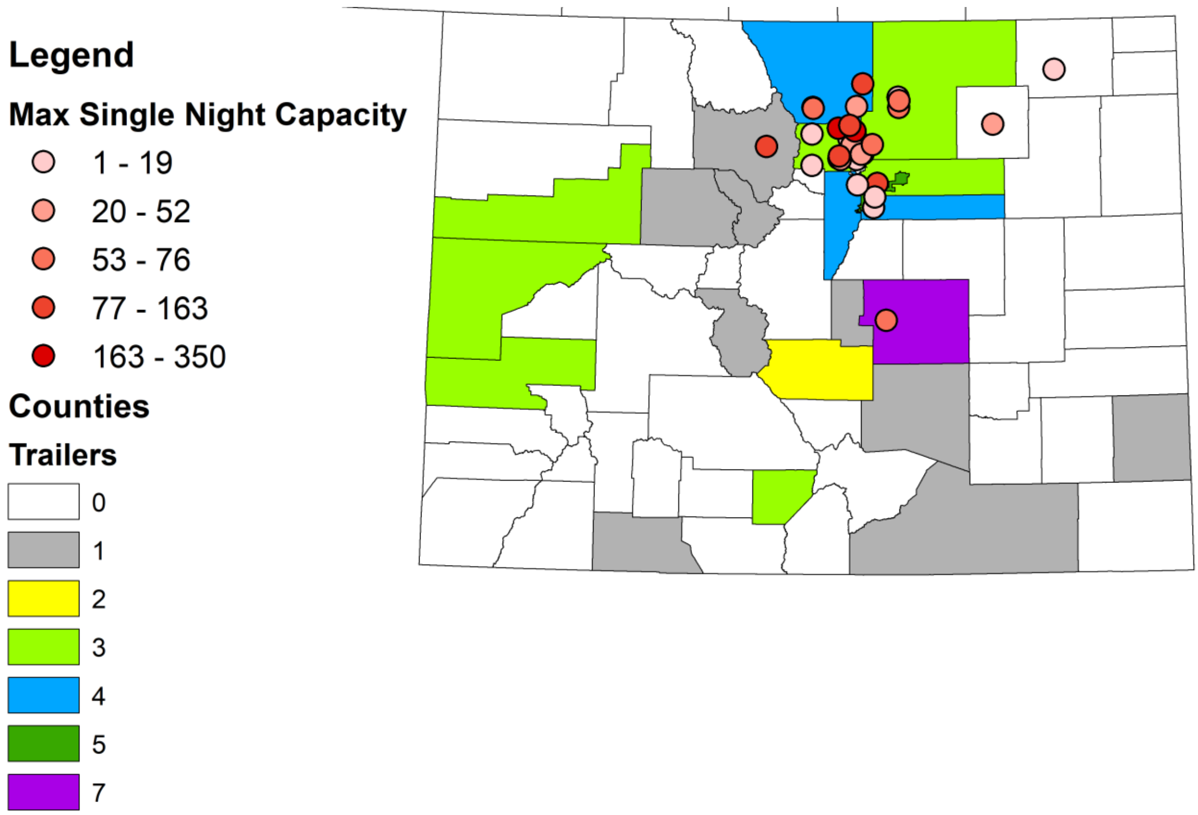


**Figure 3. Optimal trailer allocations by county and maximum single night population for shelters during 2013 floods**

Figure 4 shows the comparative results of the original allocation versus the optimized allocation, with respect to the maximum population of shelters in each county. It should be noted that the totals below include the lower-weighted adjacent trailers, not just the in-county caches and trailers.

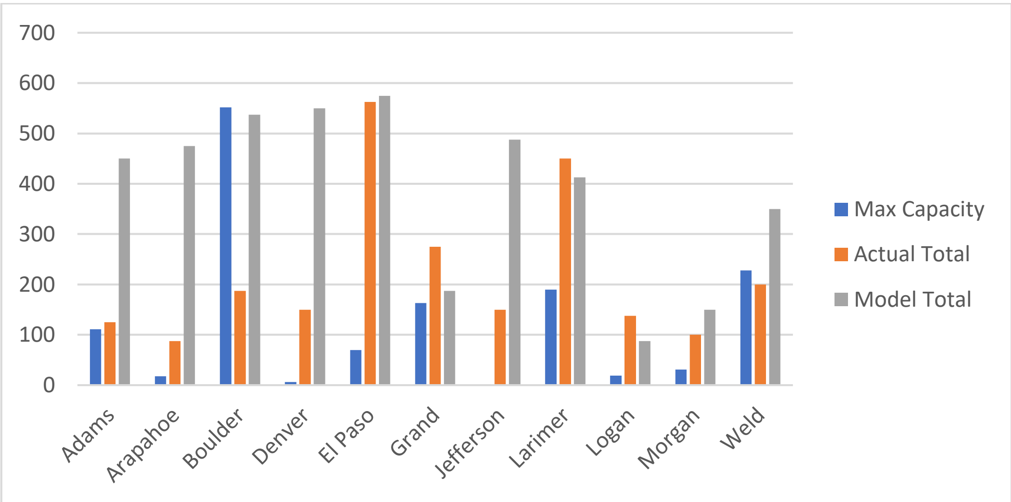


**Figure 4. Optimal versus original asset totals by county, including adjacent trailers**

## CONCLUSIONS AND FUTURE WORK

Through an analytical approach to disaster relief allocation based on three risk factors, the Red Cross hoped to improve its responsiveness for shelter openings for disaster events. This case study of the 2013 floods in Colorado illustrates this desired improvement, with an increase in in-county assets available based on the risk calculation that includes hazard likelihood and population exposure. The improved allocation of resources also led to the greater availability of adjacent trailers that were then used to meet the full needs of this event, as opposed to the 50% of in-county need that was unmet under the original allocation, even after re-assigning adjacent trailers.

As this research continues to develop, we have several areas that we would like to investigate further. First, given the Risk calculation, which is a function of Hazard Likelihood, Exposure, and Vulnerability, it is important to recognize that the Likelihood and Exposure values can be updated over time. For example, in the Southeastern United States when a hurricane is approaching, the storm track forecast can provide greater insight into the Likelihood of the event impacting a given location, as well as into the Exposure level for the population to this given event. While the flooding event in Colorado was sudden onset and there were no advance warnings, we would like to look into the role that evolving information can play in sheltering decisions. Second, the timing of the shelter openings and the consumption of assets are both issues that the case study did not address. These are important pieces of information that impact both how assets are allocated and how future asset allocations occur as the disaster event progresses through the recovery phase. Third, we did not consider the issue of restocking shelters because the focus of this initial effort has been on asset usage for the purposes of shelter openings. Moving towards a stochastic model that incorporates restocking capabilities could result in changes to the asset allocations developed so far.

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