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Investigating Tradeoffs Between Flood Control And Ecological Flow Benefits in the Connecticut River Basin

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**INVESTIGATING TRADEOFFS BETWEEN FLOOD CONTROL AND ECOLOGICAL
FLOW BENEFITS IN THE CONNECTICUT RIVER BASIN**

A Master's Project Presented By:

Jocelyn Anleitner

Submitted to the Department of Civil and Environmental Engineering of the University of
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Master of Science in Environmental Engineering

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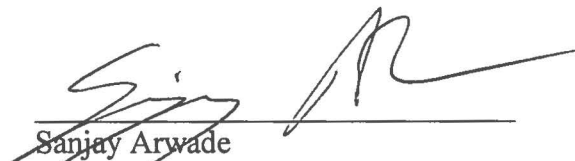
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ABSTRACT

The flow regime of the Connecticut River Basin (CRB) has been markedly altered due to the high number of impoundments reservoirs in the basin. The major services provided by these reservoirs include hydropower production, water supply, recreation and flood control. The United States Army Corps of Engineers (USACE) operates 14 flood control facilities within the basin. The storage capacities of these facilities range from 3,740 to 71,000 acre-feet. USACE is currently exploring operational alternatives that include both traditional economic benefits of the reservoirs and benefits of returning the flows of the Connecticut River and its tributaries to a more natural flow regime.

A daily time-step optimization model was created to evaluate the tradeoffs between the Connecticut River's natural environmental services and its reservoirs' multiple uses. This paper evaluates the relationships between flood control and environmental flows for aquatic species and floodplain health. Environmental flow targets, developed by aquatic scientists, biologists, and other stakeholders are used to evaluate deviations from natural flows for each ecological species of interest, for each month of the year, at critical locations throughout the basin. This paper investigates case studies on two tributaries to the Connecticut River: the West and Ashuelot. The results of this study indicate that flows in these two rivers can be returned to a more natural flow regime without significantly increasing the occurrence of flooding by adjusting existing operational storage and release targets.

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1 INTRODUCTION

There is an increased recognition within the scientific and water resources community that the ecological needs and services of a river basin should be taken into account when considering water resources infrastructure. Historically, water resource managers have strived to effectively balance multiple uses of river systems including water supply withdrawals, hydropower production, flood protection and recreational purposes. Incorporating the ecological health of the riparian ecosystem into this existing framework is an important and achievable goal. However, it has often been difficult to quantify the trade-offs between the eco-services provided by a river that is unregulated compared to a river that is operated to provide other economic benefits.

This paper proposes a methodology for addressing the inherent trade-offs between the ecosystem services provided by healthy rivers and riparian systems and those benefits provided by flood control infrastructure. Two sub-basins of the Connecticut River are selected to demonstrate this methodology. In these basins, the trade-offs between flood control and environmental flow needs are explored under a historic flow regime.

1.1 Managing rivers for ecological needs

Ecological needs of rivers have typically been accommodated by requiring a minimum release from reservoirs (Yin, Yang, & Petts, 2012; Graf, 2001; Poff, et al., 1997). While this approach is direct, it does not typically meet the diverse needs of the riverine and riparian ecosystems. Returning river systems to a more natural streamflow regime improves the health of rivers (Richter, Baumgartner, Powell, & Braun, 1996; Richter & Thomas, 2007; Richter, Warner, Meyer, & Lutz, 2006; Graf, 2001).

Standard reservoir operations often reduce the natural variability in streams by eliminating small and medium flood events and creating unnatural pulses in rivers (Richter & Thomas, 2007). Both inter and intra-annual variability of metrics, such as “magnitude, timing, frequency, duration and rate of change,” is the basis for determining the extent that flows are impacted (Richter, Baumgartner, Powell, & Braun, 1996; Mathews & Richter, 2007). While the major operational requirement of a minimum flow release addresses the quantity of flow downstream of an impoundment, the timing of flow variability is ignored with this approach (Poff, et al., 1997). Variability at different temporal scales (ranging from hourly to intra-annual) is important for the biotic communities within a healthy ecosystem; timing is critical for life cycle triggers in many aquatic species (Bunn & Arthington, 2002).

Flow extremes, such as drought and flooding, have an integral role in the health of riverine, riparian, wetland and floodplain ecosystems (Petts, 2009). Flow variability allows for ecosystem development by distributing nutrients during floods, and promotes sustainable habitat and community size during droughts (Bunn & Arthington, 2002). High flow events, specifically, have not been prioritized for protection in water management because of their inherent tradeoffs with other social benefits (Richter, 2010). Though it has been difficult to implement operational schemes that adequately reproduce natural flows and variability (Richter, 2010), various approaches using optimization have been proposed.

1.2 Multi-objective optimization in water resources management

Multi-objective optimization models have been used in water resources management for decades (Cohon & Marks, 1975). This method allows for the evaluation of tradeoffs between the potential uses of water including hydropower, water supply, flood control and recreation. By

exploring results along the “pareto optimal frontier,” decision makers and water resource managers can find operational solutions that may improve multiple water use objectives.

More recently, as the needs of the riverine ecosystems have become better defined and gained recognition, these types of models have included an objective function component to capture ecological needs. Researchers have noted the necessity to appropriately balance the traditional benefits of dams and the environmental services provided by a healthy river system (Graf, 2001). Specifically, Homa, et al (2005) demonstrated an approach that accounted for the complex, dynamic needs of rivers including a diverse hydrologic flow regime. Shiao & Wu (2007) expanded this concept by addressing the importance of intra-annual variability in their optimization approach.

2 BACKGROUND

2.1 System description

The Connecticut River is New England’s largest river, flowing just over 400 miles and encompassing a drainage area greater than 10,000 square miles. In addition to the environmental services that it provides, the river’s man-made infrastructure provides flood control, hydropower production, recreation, and water supply. There are thousands impoundments within Connecticut River Basin (CRB); while many of these are low-head, relic dams, there are over fifty reservoirs with moderate to large storage capacities.

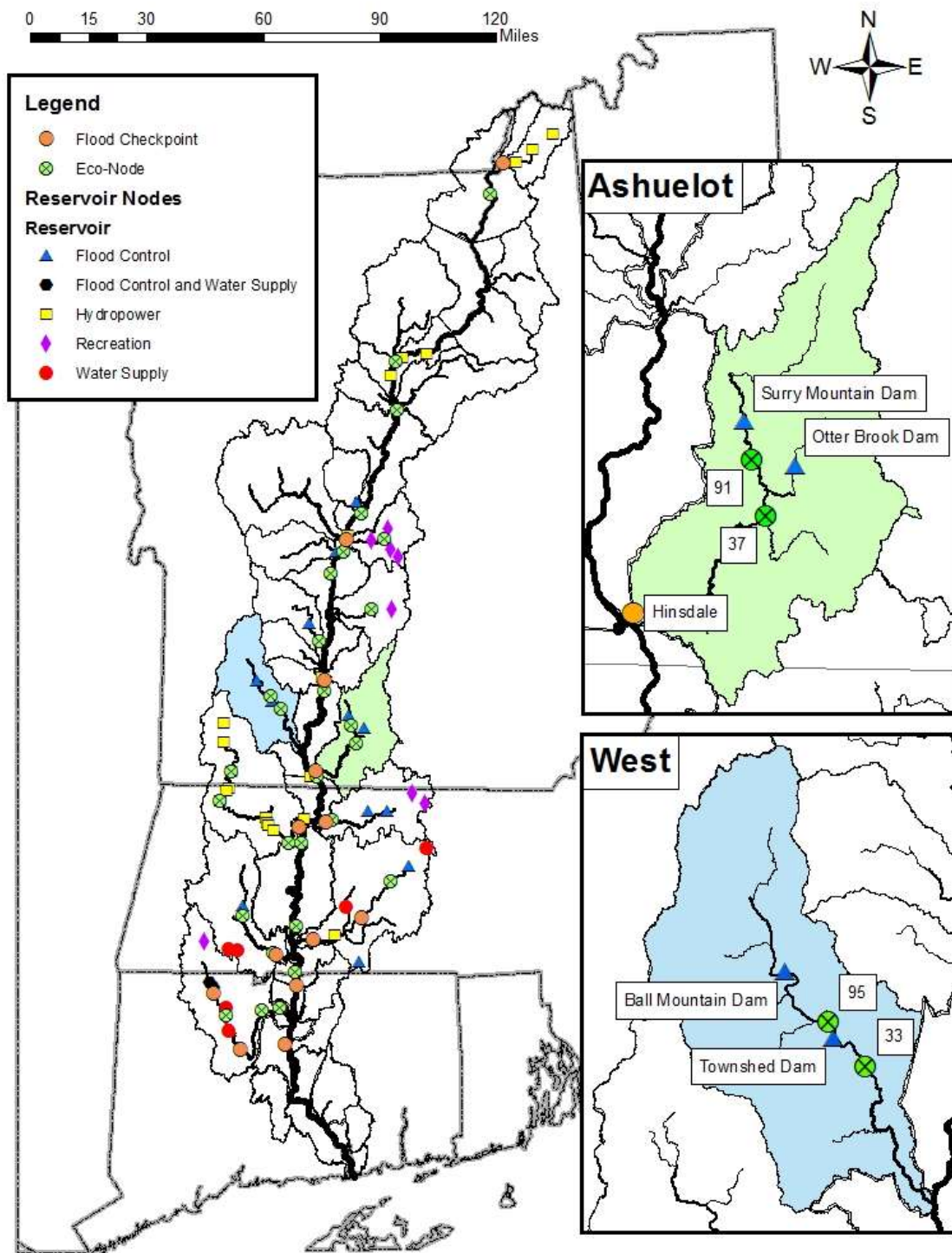


Figure 1: Map of the Connecticut River Basin showing two sub-basins: Ashuelot and West

There are fourteen flood control reservoirs in the CRB operated for flood control by the New England District of the US Army Corps of Engineers (USACE). The storage capacities of these facilities range from 3,740 to 71,000 acre-feet. These reservoirs are all located in tributaries to the Connecticut River and are operated primarily for local flood control and to reduce flood damage in the main stem of the Connecticut. This paper will specifically discuss the analysis of flood control facilities in two sub-basins: the West and Ashuelot.

2.1.1 West Basin

The West River runs approximately 50 miles through southern Vermont before joining the Connecticut River main stem near Battleboro, Vermont. Its drainage basin area is approximately 420 square miles with mostly forested ground cover. There are two USACE facilities in the sub-basin: Ball Mountain Dam and Townshend.

The construction of both facilities was completed in 1961 for flood protection along the West River as well as the main stem of the Connecticut River. Ball Mountain Dam has a capacity of 54,700 acre-feet with a permanent pool of 250 acre-feet which increases to 2,250 acre-feet for recreational purposes in the spring and summer; 54,450 acre-feet is allotted for flood storage. The entire project area covers 1,227 acres providing additional recreational area for camp sites, hunting and fishing. Ball Mountain Dam is located approximately 10 river-miles upstream of Townshend Lake.

Townshend Lake has a capacity of 33,700 acre-feet with a permanent pool of 800 acre-feet and 32,900 acre-feet are allotted for flood storage. The entire project area is 1,219 acres and provides recreational area for picnics, swimming, boating, hiking, cross-country skiing, fishing, hunting/trapping, camp sites and an open field for other activities. The stretch of river between

the two facilities is used for whitewater canoeing and kayaking with the USACE making weekend releases twice a year for this purpose.

2.1.2 Ashuelot Basin

The Ashuelot River runs 64 miles through southwestern New Hampshire before its confluence with the Connecticut River near Hinsdale, NH. Its watershed is approximately 420 square miles (New Hampshire Department of Environmental Services, 2014). The two USACE facilities in this basin are Surry Mountain and Otter Brook Dams.

Surry Mountain Dam was completed in 1941 for flood protection along the main stem of the Connecticut River as well as communities along the Ashuelot River such as Keene, NH. Surry Mountain is able to capture 31,680 acre-feet of water for flood control purposes. It has a permanent storage at the 15-ft stage which results in a 260-acre recreational pool (1,317 acre-feet). This pool is raised three feet in the winter months (to increase storage by 864 acre-feet) to prevent freezing of equipment. The project footprint encompasses 1,779 acres and includes areas for picnics, boating, hiking as well as five open acres for sports (US Army Corps of Engineers, New England District, 2014).

Otter Brook Dam was constructed on Otter Brook, which is a tributary of the Branch River (also known as Beaver Brook) and joins the Ashuelot in Keene, NH. The reservoir was completed in 1958 to prevent flooding in the same areas as Surry Mountain. Otter Brook is designed to hold 17,450 acre-feet of water for flood control. It has a 20 foot deep permanent pool used for recreation (870 acre-feet). The project area contains a state park on the North end of the lake which can be used for picnics, swimming, boating, fishing, hunting and trapping (US Army Corps of Engineers, New England District, 2014).

2.2 Basin Hydrology

Sufficient spatial and temporal historic records of flows in the CRB were not available as input for the optimization model used to explore systems operations (Section 3). However, estimated daily natural (unregulated) streamflow was calculated using the Connecticut River UnImpacted Streamflow Estimation (CRUISE) tool (Archfield & Vogel 2008; Archfield, et al., 2009; Archfield, Steeves, Guthrie, & Ries III, 2013) developed by the United States Geologic Survey (U.S.G.S.). This tool uses a regression technique that estimates a flow duration curve (FDC) for an un-gaged location (where flow information is desired) based on basin characteristics and streamflow from a nearby gaged location. This FDC is then used to develop a daily time series of flows for the location of interest.

CRUISE flows were used as inputs for the analysis in this paper. CRUISE flows were developed for the period October 1, 1960 through September 30, 2004. The optimization model, operating with calendar years, used the available data beginning January 1, 1961 through December 31, 2003 resulting in 43 years of appropriate data. Because these flows are the best available estimate for the naturalized flows in the river, they were also used as a point of comparison for the ecological flow targets (Section 3.1.2).

Average monthly inflows for the reservoirs in the West basin are presented in Figure 7 while Figure 16 presents average monthly inflows for the reservoirs in the Ashuelot basin. Average annual natural flow at the outlet of the West River is 653,000 acre-feet; the average annual natural outflow of the Ashuelot River is 492,770 acre-feet. The hydrographs indicate a typical double peaked flow, with higher flows in April and October.

3 OPTIMIZATION FRAMEWORK

The Connecticut River Optimization Modeling Environment (CROME) is an optimization model developed in the well establish framework of a multi-objective linear program. CROME was originally developed to analyze trade-offs between various operational objectives throughout the CRB: hydropower production, recreational storage targets, municipal water supply, flood control and environmental targets. In this paper, the model was broken apart to isolate the two sub-basins of interest (West and Ashuelot) and the two objectives of interest (flood control and ecological targets). There are two main components of any linear program: an objective function, whose value is maximized or minimized, and constraints that bound the objective function value.

3.1 Objective Function

The basic structure of the CROME model is:

$$\min Z = \sum_{t=1}^T \sum_{i=1}^N c_i \times f_{t,i}(x_{t,i})$$

(Equation 1)

Subject to:

$$\mathbf{Ax} \leq \mathbf{b}$$

where Z is the objective function value, c_i is the weight coefficient of the i^{th} decision variable, $f_{t,i}(x_{t,i})$ is the penalty function for the i^{th} decision variable at time-step t , \mathbf{x} is the matrix of decision variables \mathbf{A} is a matrix of constraint coefficients and \mathbf{b} is the “right-hand-side” vector of the constraint matrix.

In the version of CROME used in this analysis, there are two primary penalty functions within the objective function: flood control and environmental flows. The decision variables in the model include: reservoir releases and reservoir storages, which result in flows at eco-nodes

and flood gages. In addition, the model is constrained by continuity equations and physical constraints of reservoirs.

3.1.1 Flood Control Objective

To analyze flooding in CROME, appropriate locations were chosen to represent streamflow along the Connecticut River and its tributaries. These flooding “checkpoints” were assigned a flooding flow threshold based upon USACE calculations of potential flooding at “pinch points.” These pinch points included private property, camp sites and other locations prone to flooding. In addition to a flood-flow threshold, a warning flow threshold was also calculated. These warning flow thresholds are lower than the flood-flow threshold and represent flows that should be avoided when possible due to potential property damage. Weights for avoiding flooding flows were significantly larger than those for avoiding warning flows.

The West sub-basin did not have an assigned flood-gage checkpoint in CROME. A proxy flood gage was created at the outlet of the sub-basin that was downscaled from on the closest downstream main stem flood gage based on average annual flows (the Connecticut River at Montague City, MA). All flood gage checkpoints discussed in this paper, along with their flood and warning flow thresholds, are included in Table 1.

Table 1: Flood gage checkpoint name, location, warning and flood flow thresholds

Sub-Basin	Gage Name/Location	USGS Gage No.	Warning Flow (cfs)	Flood Flow (cfs)
West	Proxy/Outlet	N/A	4,127	5,770
Main stem	Connecticut River at Montague City, MA	01170500	64,200	89,750
Ashuelot	Ashuelot River at Hinsdale, NH	01161000	6,170	9,360

3.1.2 Environmental flow Objective

While traditional environmental flow objectives can be characterized as fixed, minimum flow targets, this project uses a temporally and spatially dynamic ecological target. It has been established that flows encapsulating a full range of natural variability are important for a thriving, healthy aquatic and riparian ecosystems; this includes metrics such as magnitude, duration, frequency, timing and rate of change of flows. This model uses a dynamic, concave penalty function as used in previous related projects (Steinshneider, Bernstein, Palmer, & Polebitski, 2013; Pitta, 2011; Bernstein, 2013). This framework emphasizes more natural flows by allowing for some deviations from estimated natural flows; these allowable deviations were determined by local aquatic biologists and scientists.

A series of workshops and webinars were held to elicit input from stakeholders—specifically aquatic scientists and biologists. This group agreed that a return to more natural flows would be beneficial for most species in the region. With this goal, acceptable percent deviations from natural flows were determined for each ecological species of interest for each month of the year, at all eco-nodes. These recommendations were used to develop the quantitative bounds used in the model.

The allowable deviations are unique for each species but also vary by month as well as flow decile. Monthly flow deciles were calculated using natural CRUISE flows (Section 2.2) at each eco-node to divide the flow into ten ranges. This provided the aquatic biologists and scientists a more specific way to define allowable flow deviations. For example, low flow events in January may be more important to the health of resident fish than moderate flow events in June; in this case a smaller allowable deviation (say, 1%) are allowed without penalty for a low flow event in January while up to 25% deviations from natural flow are allowed without penalty for medium

flow levels in June. Flows beyond this allowable deviation incur a penalty within the objective function equal to the weight S1 (equal to 1) multiplied by the magnitude of the deviation.

These ecological targets are further constrained by the addition of a second tier of allowable bounds. Flows beyond this second tier are penalized twice as heavily as flows beyond the first allowable bound (weight of S2=2). Figure 2 shows a sample of penalty functions for one species for two months that happen to have the same allowable deviations. Each of the four points in Figure 2 is referred to as the inflection points of the penalty function.

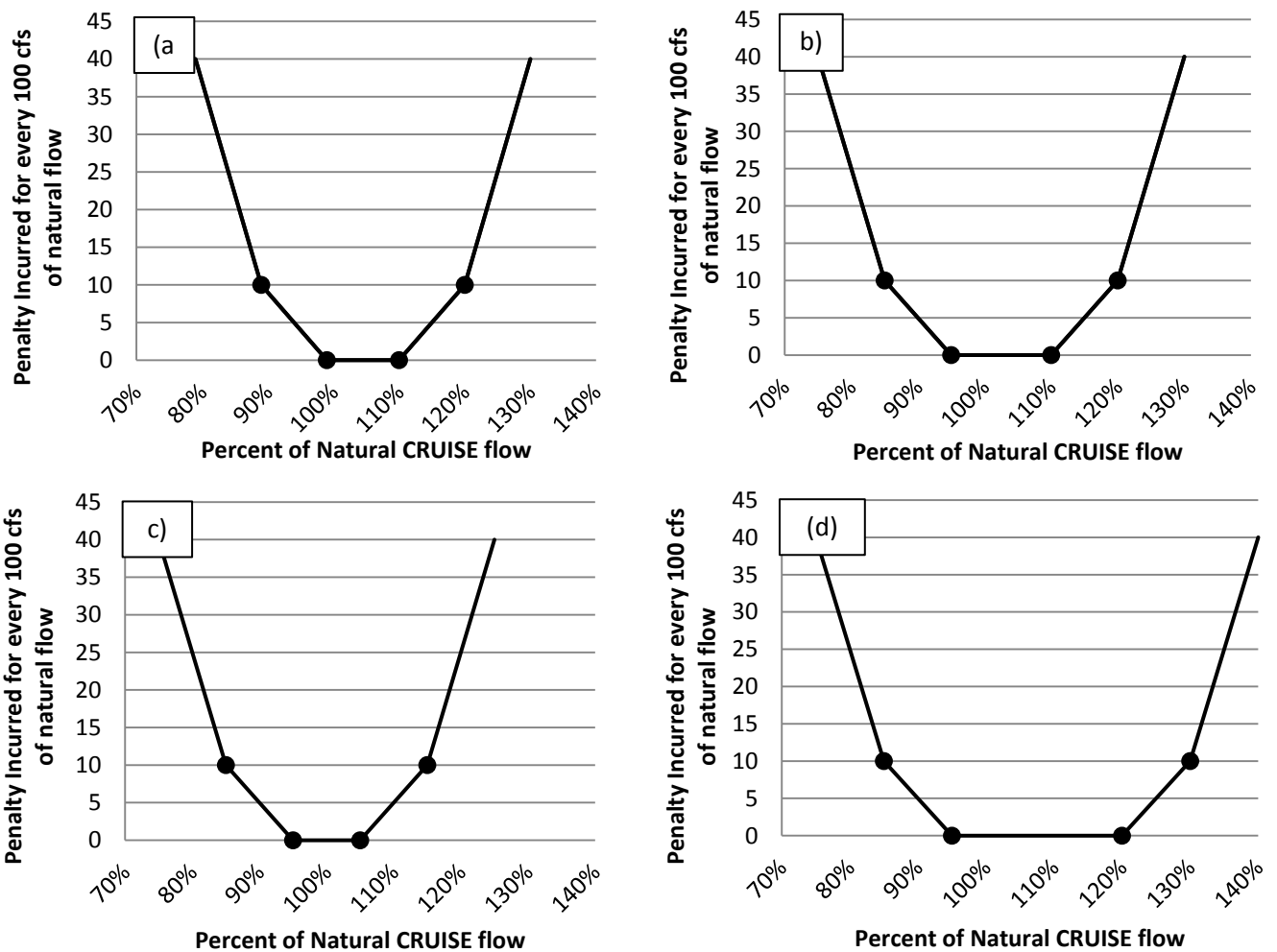


Figure 2: Convex penalty functions for resident fish for the months of January and February: (a) Minimum-Q90, (b) Q90 – Q70, (c) Q70-Q30, and (d) Q30-Maximum

To account for multiple species at a single location, each of the four inflection points that define every penalty function is considered and the most constraining value from all species under consideration is used as the penalty function in the model. In this way, the needs of all species can be met as the model’s objective function is optimized when flows are within the bounds of all species’ needs.

In summary, for each day of the year, for each eco-node, the penalty function is determined based on the month of the year, the flow decile of the estimated natural flow within that month, and the species under consideration at that location. The natural flow at the eco-node for each day is assigned the appropriate flow decile for that month and the most constraining four inflection points are used to develop the penalty function. The difference between the modeled flow and the allowable deviation is then calculated; any differences beyond the allowable deviations are penalized in the objective function and weighted by the values of S1 and S2.

The ecological target is spatially dynamic by applying this framework to 28 locations of importance in CROME, as defined by local aquatic biologists and scientists, hereafter referred to as eco-nodes. While these eco-nodes are distributed throughout the Connecticut River Basin and along the main stem of the Connecticut River, this study focuses on those eco-nodes contained within the sub-basins of interest (Table 2).

Table 2: Eco-node numbers evaluated in this report, the species they account for, and their watershed location

Eco-Node Number	Targets					Watershed
	<i>Floodplain</i>	<i>Mussels</i>	<i>Tiger Beetles</i>	<i>Diadromous Fish</i>	<i>Resident Fish</i>	
33	X	X		X	X	West
37	X	X			X	Ashuelot
91	X	X			X	Ashuelot
95	X	X			X	West

3.2 Constraints

The model is constrained by the physical and operational limits of the reservoirs and continuity equations. The reservoir capacities cannot be exceeded and inactive storages (for sedimentation pools and conservation pools that are smaller than 5% of total capacity) must be met (Table 3). Other storage targets, such as recreation or other purposes, are accounted for in the objective function.

Table 3: Storage Constraints on flood control reservoirs

Sub-Basin	Dam	Capacity (acre-feet)	Inactive or Non- Useable Storage (acre-feet)	Target Storage (acre-feet)
West	Ball Mountain	54,700	250	<i>Oct-April: 520 May-June: 250 July-Sept: 2,250</i>
	Townshend	33,700	800	0
Ashuelot	Surry Mountain	33,011	1,317	<i>Dec-May: 2,181 June-Nov: 1,317</i>
	Otter Brook	18,320	870	870

In addition to storage constraints, reservoirs must be operated within their maximum and minimum release rates (Table 4). The maximum releases are defined by the physical constraints of the system while the minimum required releases are defined within operational licenses to meet minimum ecological needs downstream. Further, the reservoirs are limited to historic ramping levels such that reservoir draw-downs are not made more quickly than is practical or physically allowed.

Table 4: Release constraints on flood control reservoirs

Sub-Basin	Dam	Maximum Release Rate (cfs)	Minimum Release Rate (cfs)		
			<i>October-March</i>	<i>April-May</i>	<i>June-September</i>
West	Ball Mountain	5,000	170	690	90
	Townshend	9,000	280	1,100	140
Ashuelot	Surry Mountain	<i>October-April: 1,250</i> <i>May-September: 850</i>	100	400	75
	Otter Brook	650	50	200	25

3.3 Experimental Design

This analysis uses a daily time-step optimization model (CROME) created in the LINGO™ software environment. Using the CRUISE tool, daily streamflow was estimated for numerous locations throughout the basin and used as inflows to the model (Archfield, Steeves, Guthrie, & Ries III, 2013).

The basic experimental design applied in this research using CROME is the following: daily flows (from 1961-2003) were incorporated into the model to determine the range of impacts on ecosystem and other societal services provided by water resources infrastructure (specifically flood control) by varying the objective function in the model to explore various operational changes. Because the active storage in the reservoirs for these basins is small relative to their annual flows (flood control storage is less than 15% of average annual flows in both the West and Ashuelot basins), and to limit the size of the optimization model, individual years were runs sequentially with one year optimized at a time. The ending storage in reservoirs for one year is set as the beginning storage for the following year. A “status quo” base run for the system was established by operating the system to minimize deviations from storage targets and other historic operating goals. The status quo runs did not attempt to meet any environmental targets in the system. Next, an “environmental flow target” (or e-flow target) base run was established by

maximizing the system's ability to meet pre-defined environmental flow targets. For the “e-flow target” runs, non-USACE facilities were constrained to perform as they had in the status quo run while USACE storage and flood gage target weights were turned off. The results from this run were used to determine optimal operations for meeting eco-node targets if only USACE facilities altered operations to meet eco-node flows.

While CROME was originally developed for full-basin analyses of the CRB, this study created isolated sub-basin optimization models—one for the West and one for the Ashuelot. It was determined that runs focusing on a single tributary basin would provide more useful insight than a CRB scale run. A full basin run includes main stem ecological and flood gage targets, which were already shown to have little to no improvement in previous work, and could minimize the ability of the facilities to meet local eco-node or flood gage targets.

After the status quo and e-flow target runs were completed, the trade-off between maintaining environmental flows at their targets and minimizing flows above a flood gage threshold were explored. Flood gage penalties calculate the magnitude of flows beyond the flood threshold for each time step and multiply it by a weight. Ecological penalties were calculated by finding the difference in flows above or below the allowable deviations (as defined in section 3.1.2) from CRUISE estimated natural flows. These deviations from specific allowable ranges (which varied by species, time of year, and magnitude of flow) are multiplied by a weight in the objective function. For each point on the trade-off curve, the cumulative 43 years' worth of penalties were calculated for both the ecological penalties and the flood gage penalties. The trade-off curve was constructed by changing the ecological penalties from objectives into constraints while still minimizing the flood deviations.

To calculate the values used in this trade-off, ecological penalties under the status quo and e-flow target runs were summed on an annual basis because CROME optimizes individual years. Then, for each tradeoff run, values were linearly interpolated between these two extremes for each year of the investigation. The model was then constrained to limit the ecological penalties to be less than or equal to that interpolated value while still maximizing flood control performance. The points for interpolation were chosen to ensure even distribution between the status quo and e-flow target runs; these were not consistent across the sub-basins of investigation. This ensured that a full spectrum of operations could be investigated during the process. The shape of the trade-off curve indicates whether or not significant improvements in ecological flows can be achieved without a loss of flood control performance.

3.4 Model Metrics

Five primary metrics were used to evaluate the impacts of changing operating policy in the system:

- 1) Sub-basin scale tradeoff curve between flood penalties and e-flow target penalties,
- 2) Average deviations from natural flow at each eco-node,
- 3) Number and magnitude of flooding events,
- 4) Average daily reservoir storage levels, and
- 5) Ratio of reservoir inflows to releases.

Each of these metrics is described in the subsequent sections.

3.4.1 Tradeoff Curve

While CROME calculates penalties incurred by the two objective function terms (flood control and environmental flow targets), these raw penalty values are not commensurate.

CROME calculates weighted penalties based upon the magnitude of deviation from a target in cubic feet; these are then summed over 365 days per year, for 43 years (as described in sections 3.1.1 and 3.1.2). The values in these tradeoff curves have not been normalized (by drainage area, average flow, or other appropriate metric) so the values should not be compared across basins.

3.4.2 Average deviations from natural flow at eco-nodes

To determine if significant changes at eco-node locations could be achieved with a change in operational regime, the average deviations from natural flows for each month were calculated for the status quo and e-flow target runs. These values were calculated by determining the difference between each modeled flow value and the CRUISE estimated natural flow at the eco-node of interest for each day and taking the average values for each month. Fewer deviations imply an improved flow regime.

3.4.3 Number and magnitude of flooding events

To quantify the frequency and size of flood events, the number of days with flows above a flooding threshold was compared for various trade-off runs. These values are the total number of days over a 43 year model run with days above the flooding threshold. In addition to this frequency evaluation, it was important to compare the relative magnitude of floods. For each trade-off run, the peak and median flood magnitudes were calculated. To further qualify the flooding magnitude, a metric called the maximum “distributed” flood magnitude was also calculated. This was done to illustrate how the flood release might be handled during actual operations. Due to the structure of the flooding penalty function, any flows beyond the flooding magnitude are penalized equally; therefore, the model can behave in unrealistic ways by releasing a very large flood flow one day and a flow just above the flooding threshold the next. If

this happened during the peak flow event listed in the “maximum flood magnitude” column, a post-processing analysis averaged the two events to find the “distributed” flood maximum.

3.4.4 Reservoir Storage Levels

Once the trade-offs between flooding and ecological flows are performed, changes in reservoir storages were analyzed. For each reservoir under investigation, historic storages (when available) were compared to various model run output values. These modeled outputs are also compared to the target storages used in the model. This information was used to determine if significant changes to current operational rules could be made and if so, what they should be.

3.4.5 Ratio of reservoir releases to inflows

Finally, to develop specific operational recommendations, the ratio of releases to inflows was calculated for each reservoir. These were then sorted by month and into three categories of flow regime: low flows (lowest 15% of inflows), moderate flows (middle 70% of inflows), and high flows (highest 15% of inflows). Box plots were used to display this data in order to show the full spread of model output as outliers can provide key operational insights for this type of analysis.

4 RESULTS & RECOMMENDATIONS

4.1 West Sub-Basin Results

The tradeoff curve for the West sub-basin illustrates an opportunity for ecological penalties to be reduced nearly 75% before significant increases in flooding penalties occur (Figure 3). This region of the curve (points B and C) may represent a reasonable “inflection” point where plausible recommendations for re-operation can be explored.

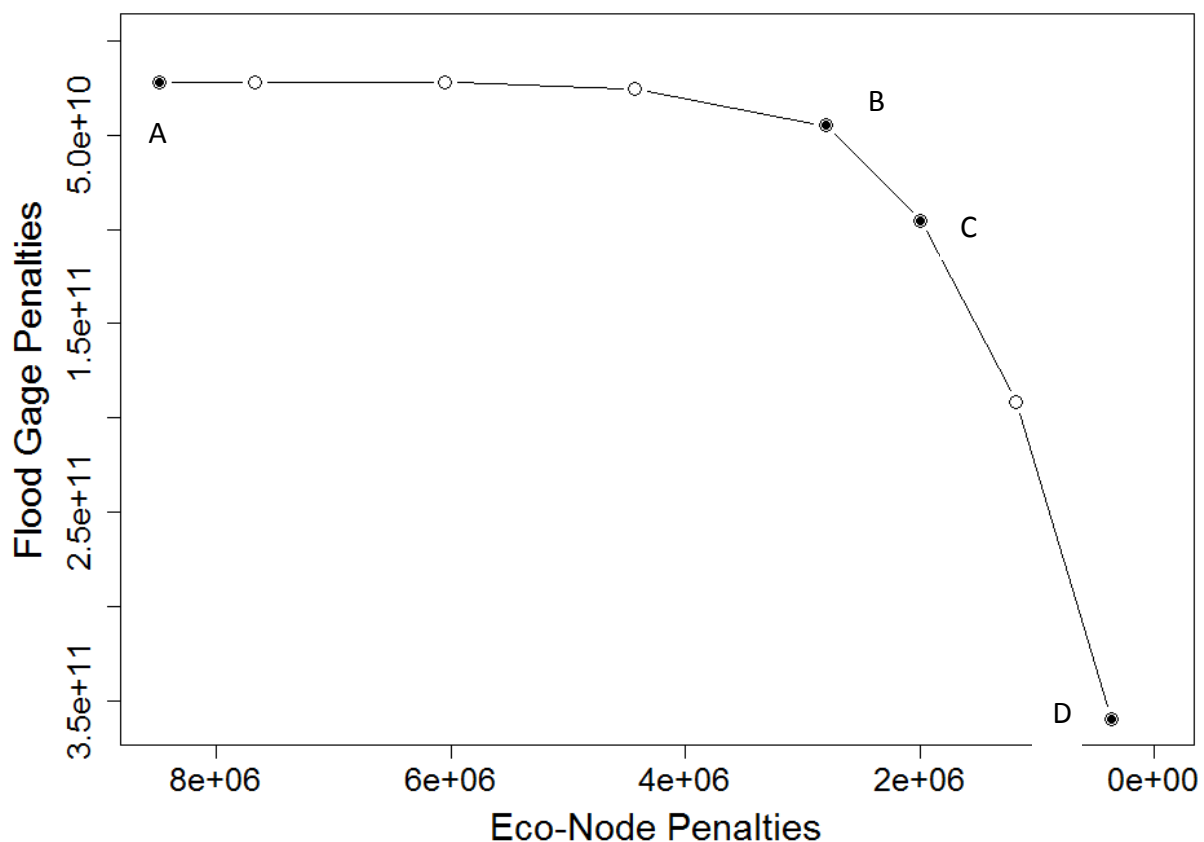


Figure 3: West sub-basin tradeoff curve

Deviations from natural flows at eco-nodes under the status quo run (point A), on average, were found to be most significant in May and September at both eco-node 33 and 95 with flows being between 5 and 10% higher than natural (Figure 4). Both eco-nodes also show lower than natural flows in February and March, although these flows are still within 5% of natural. These deviations can be understood after viewing the daily average storages in both reservoirs (Figure 5). The status quo storage levels peak in mid to late April and the reservoirs are quickly drawn-down (emptied) in early May, explaining the higher than natural flows occurring at both eco-nodes at this time. Historically, flows are at their minimum in September so as the recreation pool at Ball Mountain Dam is lowered in mid-September, these additional releases are causing

the deviations at both eco-nodes in the system. Because deviations are presented as a percent of natural (Figure 4), any changes in flow when natural flows are so small (a few hundred cfs) results in a large percent deviation.

At both eco-nodes, the flows under the e-flow target run are much closer to natural flows (represented by 0% flow alteration from estimated natural flows). Completely natural flows were not achieved in this run because the model is still constrained by the minimum and maximum releases from each reservoir.

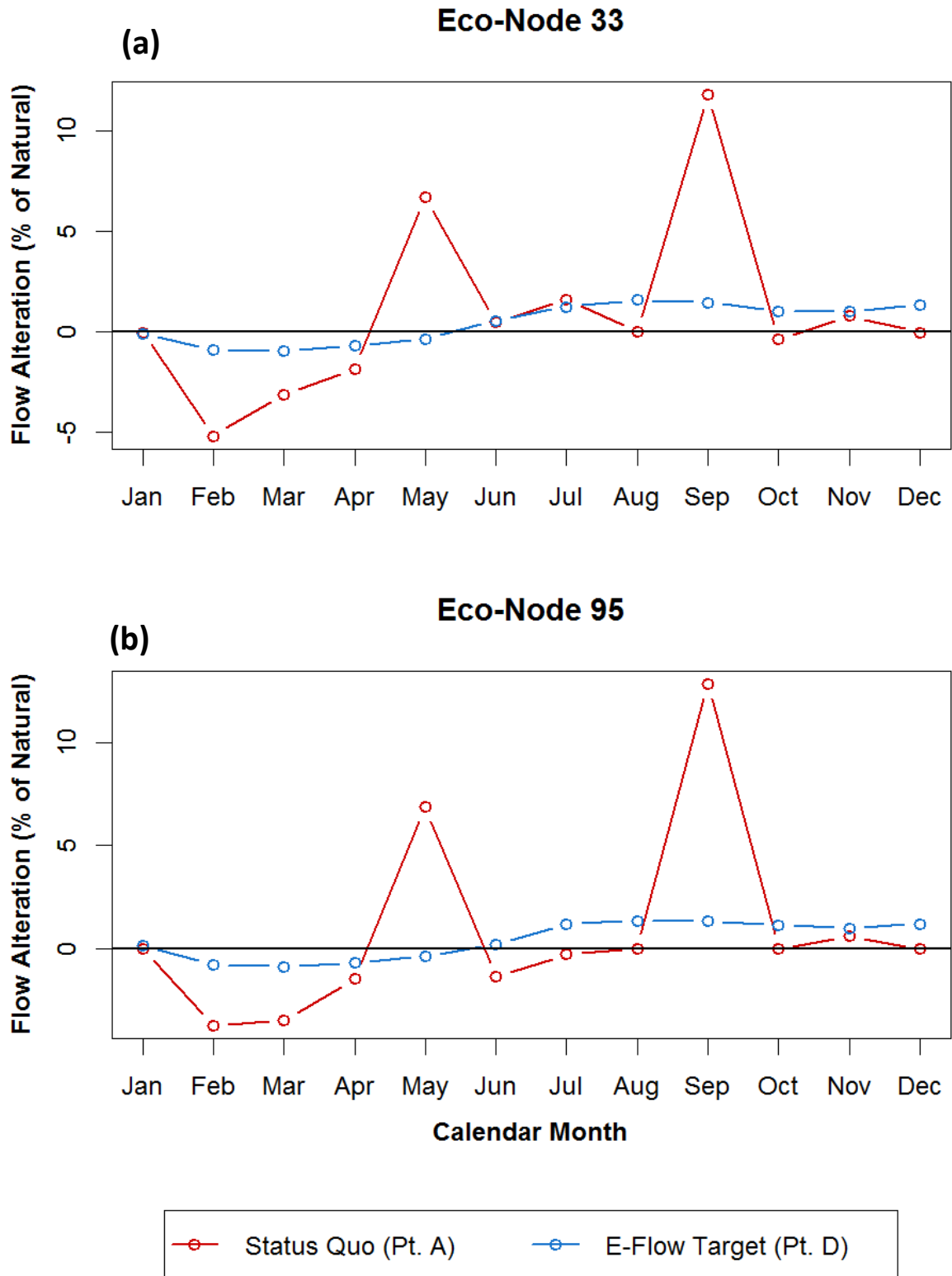


Figure 4: Average monthly flow deviations from natural CRUISE flows at Eco-Nodes (a) 33 and (b) 95 in the West Sub-Basin under Status Quo and E-Flow Target runs

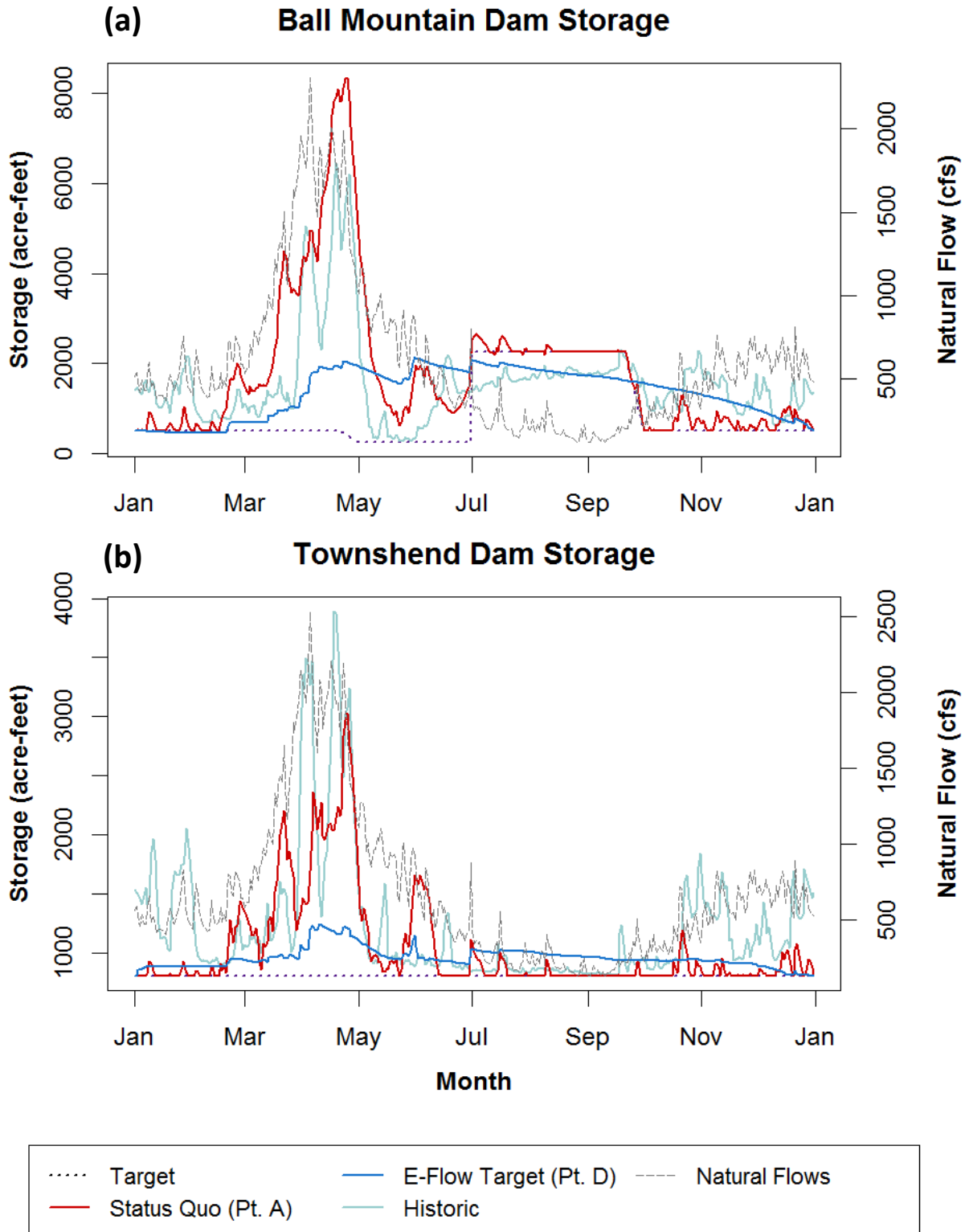


Figure 5: Average daily storage patterns (left axis) in West Sub-Basin flood control reservoirs, (a) Ball Mountain Dam and (b) Townshend Dam, for USACE-defined Target storage levels, Status Quo and E-Flow Target model runs, and historic storage levels. Right-hand axis presents average daily natural flows.

There is a significant trade-off between flood penalties and maintaining natural flows. The flooding penalty increases due to more frequent and larger events (Table 5). The number of flooding events increases as expected, as well as the maximum flooding magnitude over the various tradeoff runs. The median flood magnitude decreases as one moves from left to right (Point A to Point C) on the trade-off curve before increasing (between ECO_RUN_0.20 and Point D). This situation can be explained by the higher occurrence of flooding events near the flooding threshold. Because a proxy flood gage target was used in the West sub-basin, these occurrences should be interpreted as high flow (but not flooding) events.

Table 5: Number of and average magnitude of flow events above the flooding threshold (5,770 cfs) at the outlet of the West Sub-Basin over the 43 years of model runs

Model Run Name	Occurrences	Maximum Flood Magnitude	Maximum Distributed Flood Magnitude	Median Flood Magnitude	Occurrences within 10% of Max. Magnitude
Status Quo (Pt. A)	31	13,729	13,729	6,592	1
ECO_RUN_0.90	32	13,729	13,729	6,549	1
ECO_RUN_0.70	40	13,729	13,729	6,023	1
ECO_RUN_0.50	79	18,144	12,738	5,770	1
ECO_RUN_0.30 (Pt. B)	194	18,144	12,923	5,770	1
ECO_RUN_0.20 (Pt. C)	209	18,144	15,093	5,770	2
ECO_RUN_0.10	217	18,436	18,413	5,770	4
E-Flow Target (Pt. D)	220	18,436	15,959	8,000	4

The average daily storage levels calculated in the status-quo run are similar to the average daily historic storage levels in both of the reservoirs in this sub-basin (Figure 5) which is a further confirmation that the optimization model status-quo run is adequately constrained and modeled. While there is a significant difference in storage levels between status quo, e-flow target, and other trade-off runs (Figure 6), compared to the capacity of the reservoirs (54,700

acre-feet for Ball Mountain and 30,700 acre-feet for Townshend), these changes are a small percentage.

For Ball Mountain Dam, model results indicate that storing less of the high spring flows would provide a more natural flow region at eco-node 95. The average high flow at eco-node 95 is less than half of the flooding threshold (5,770 cfs), so passing these high flows normally will have no damaging effects (Figure 5 and Figure 6). Additionally, model results indicate that any flows that are stored should be released more gradually than has been done historically which would prevent any unnatural pulses in flow from occurring downstream.

At Townshend, a different storage pattern emerges. The two trade-off runs have storage levels that are, on average, larger than in the status quo run during spring high flows. Again, it should be emphasized that while this is a significant difference between model runs, the highest storages seen in Figure 6 are approximately 25% of capacity (30,700 acre-feet). Townshend is capturing those larger releases being made at upstream Ball Mountain Dam and slowly releasing them throughout the year. Because the eco-targets are similarly weighted in the objective function, the model can more easily achieve natural flows at eco-node 95 (located between the two reservoirs) than at the furthest downstream eco-node. Townshend is able to capture these higher inflows and slowly release them over time to minimize deviations from natural flows at eco-node 33 without causing flooding events at the basin outlet.

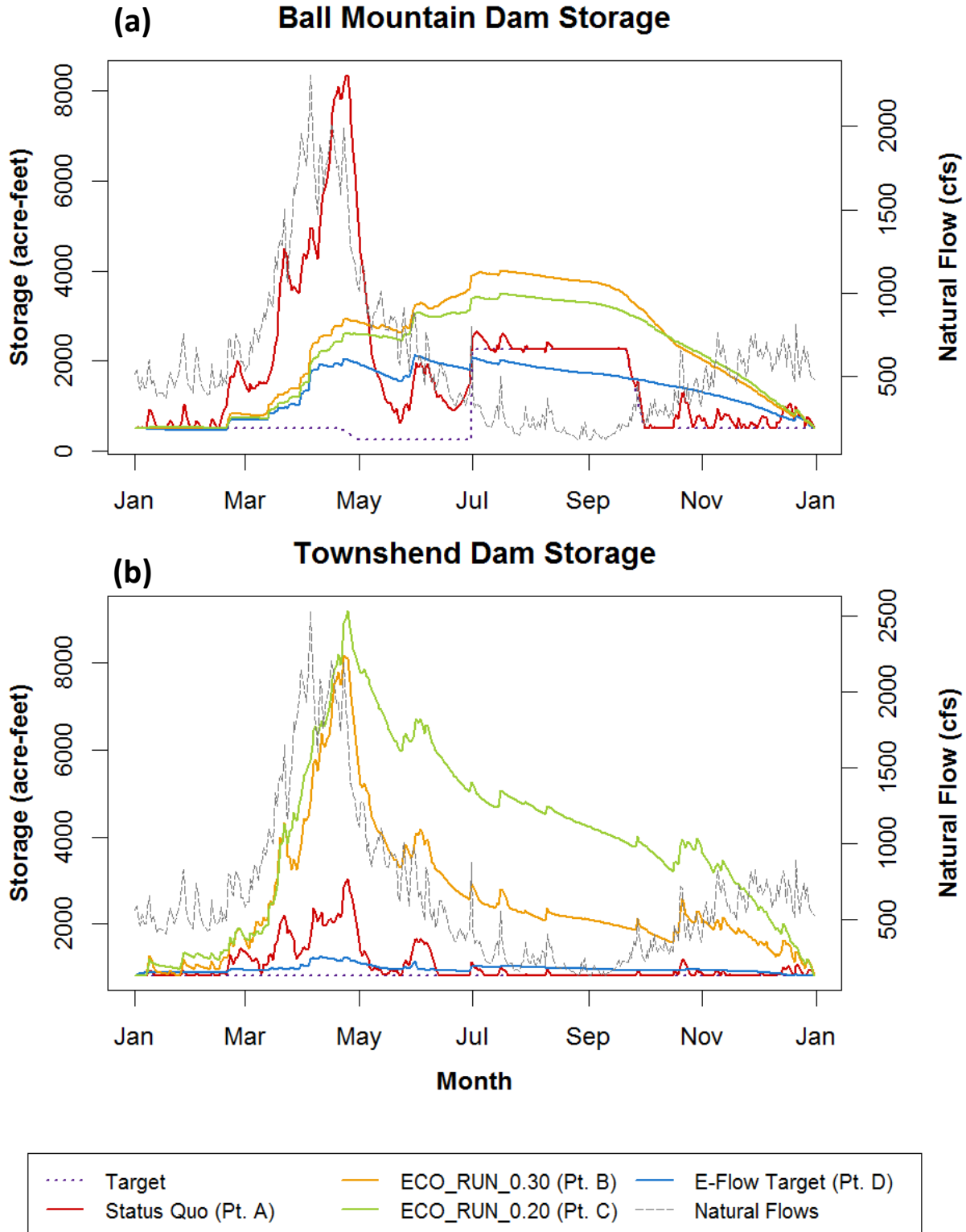


Figure 6: Average daily storage patterns (left axis) in West Sub-Basin flood control reservoirs, (a) Ball Mountain Dam and (b) Townshend Dam, for the four modeled tradeoff curve points of interest as well as USACE defined target storage levels. Right-hand axis presents average daily natural flows.

4.2 West Sub-Basin Recommendations

There are opportunities to re-operate reservoirs in the West sub-basin to achieve more natural flows along the West River without major losses to flood control protection based upon the historical hydrologic record. The optimization model results suggest that Ball Mountain Dam could allow all but flood flows to pass through the reservoir in April and May and Townshend could capture most of these releases. Ball Mountain Dam could raise its recreational storage target by approximately 1,000 acre-feet and have a more gradual filling and drawdown period to minimize deviations from the natural flow regime. Townshend, too, should more gradually draw down the reservoir after capturing the spring high flows.

To provide more specific recommendations, the monthly ratios of releases to inflows for each reservoir were examined. Figure 8 and Figure 9 present the ratio of releases to inflows for Ball Mountain Dam under four model runs of interest (as identified in Figure 3) and Figure 10 and Figure 11 present the same metric for Townshend Dam (additional figures showing greater resolution can be found in Section 7). Inspection of this metric leads to the recommendations in Table 6 based on inflow levels; numbers in the “- %” columns are the allowable negative deviations from inflow while numbers in the “+ %” column are the allowable positive deviations from inflow. For example, for Ball Mountain Dam, under medium flow conditions in June, up to 50% of inflows can be stored (resulting in releases being 50% less than the inflow volume) and up to an additional 100% of water can be released compared to inflow (or double) in order to drain down the reservoir.

Table 6: Monthly recommended releases for West reservoirs under three flow regimes. Low Flows are defined as the lowest 15% of reservoir inflows, Med. Flows are defined as the middle 70% of reservoir inflows, and High Flows are defined as the highest 15% of reservoir inflows. Values shown are the allowable percent deviation from inflows.

Month	Ball Mountain Dam						Townshend					
	Low Flow		Med Flow		High Flow		Low Flow		Med Flow		High Flow	
	- %	+ %	- %	+ %	- %	+ %	- %	+ %	- %	+ %	- %	+ %
March	0	0	0	20	40	10	0	10	0	200	80	100
April	0	0	0	40	50	0	0	10	0	200	90	50
May	0	20	0	40	40	20	0	20	0	150	50	75
June	0	15	50	100	50	100	0	10	0	75	80	200
July	0	15	70	25	70	25	0	10	0	20	50	175
August	0	15	0	10	0	10	0	10	0	20	15	15
Sept	0	40	0	75	0	25	0	20	0	15	25	100
October	0	30	0	50	0	15	5	10	10	20	75	125
November	0	40	0	50	5	10	5	5	10	15	50	50
December	0	35	0	50	20	75	0	10	0	40	75	200
January	0	0	0	35	5	10	0	0	0	15	80	150
February	0	15	0	35	40	10	0	0	0	25	80	100

From Table 6, some general trends emerge. Except during high flow events, reservoirs should pass nearly all of their inflows. During low flow periods, any reservoir drawdowns should be made to equalize releases and inflows (with the exception of Ball Mountain Dam during the fall which can be attributed to their need to draw down their recreational pool). There is more flexibility for pool draw down in moderate flow times. Not surprisingly, high flow events in the spring and early summer require even greater operational flexibility with Townshend holding back up to 90% of inflows and Ball Mountain catching up to 75% of inflows. Consequently, the releases for this flow regime may also need to be much greater to drain the reservoir from these high flow events. However, as shown in the reservoir storage plots, this should be done as gradually as possible; keeping releases equal to inflows as often as possible should be the ultimate goal.

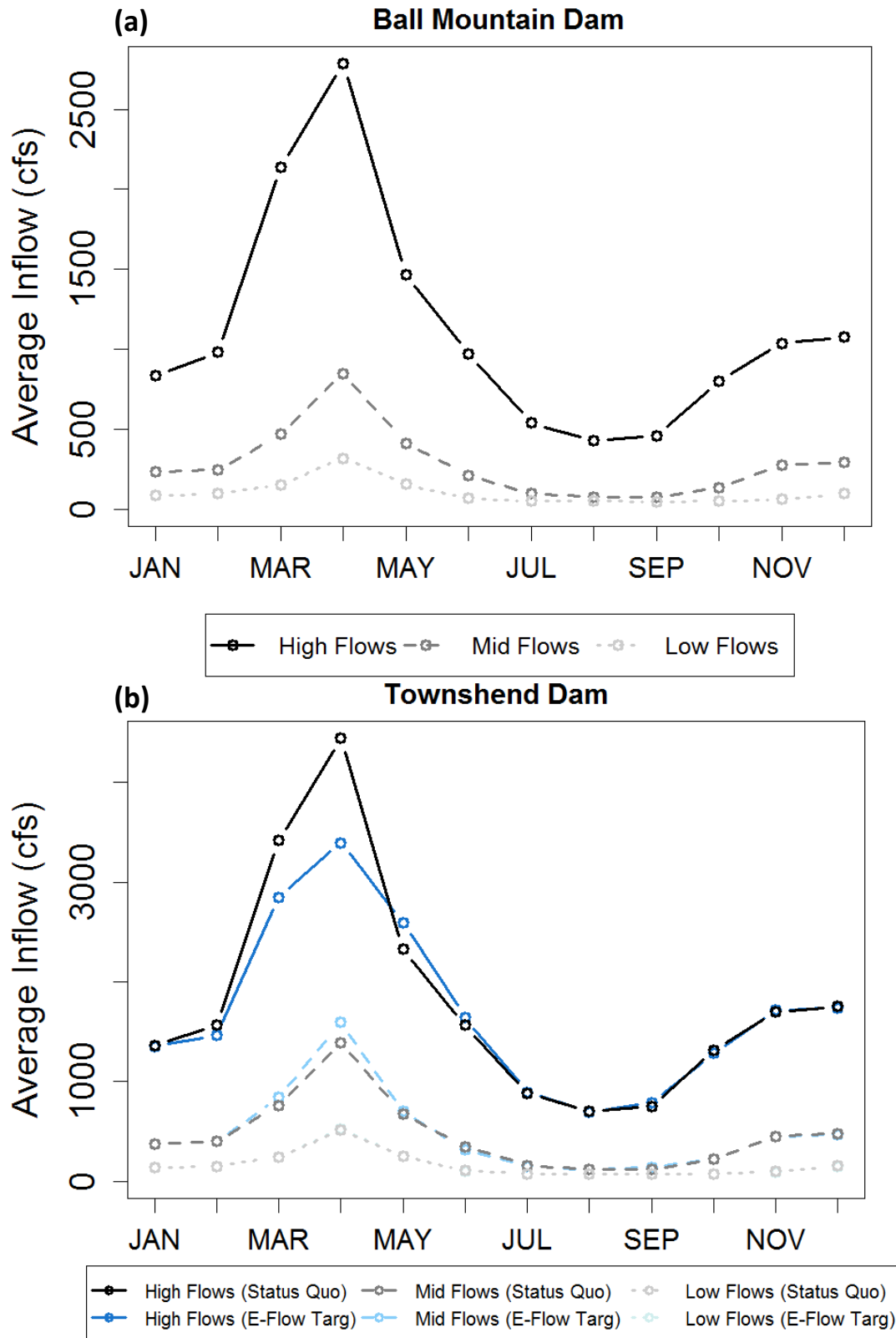


Figure 7: Average monthly reservoir inflows ranked by lowest 15%, middle 70% and highest 15% for (a) Ball Mountain Dam and (b) Townshend Dam. Note that because Townshend is downstream of Ball Mountain, there are different values for different model runs

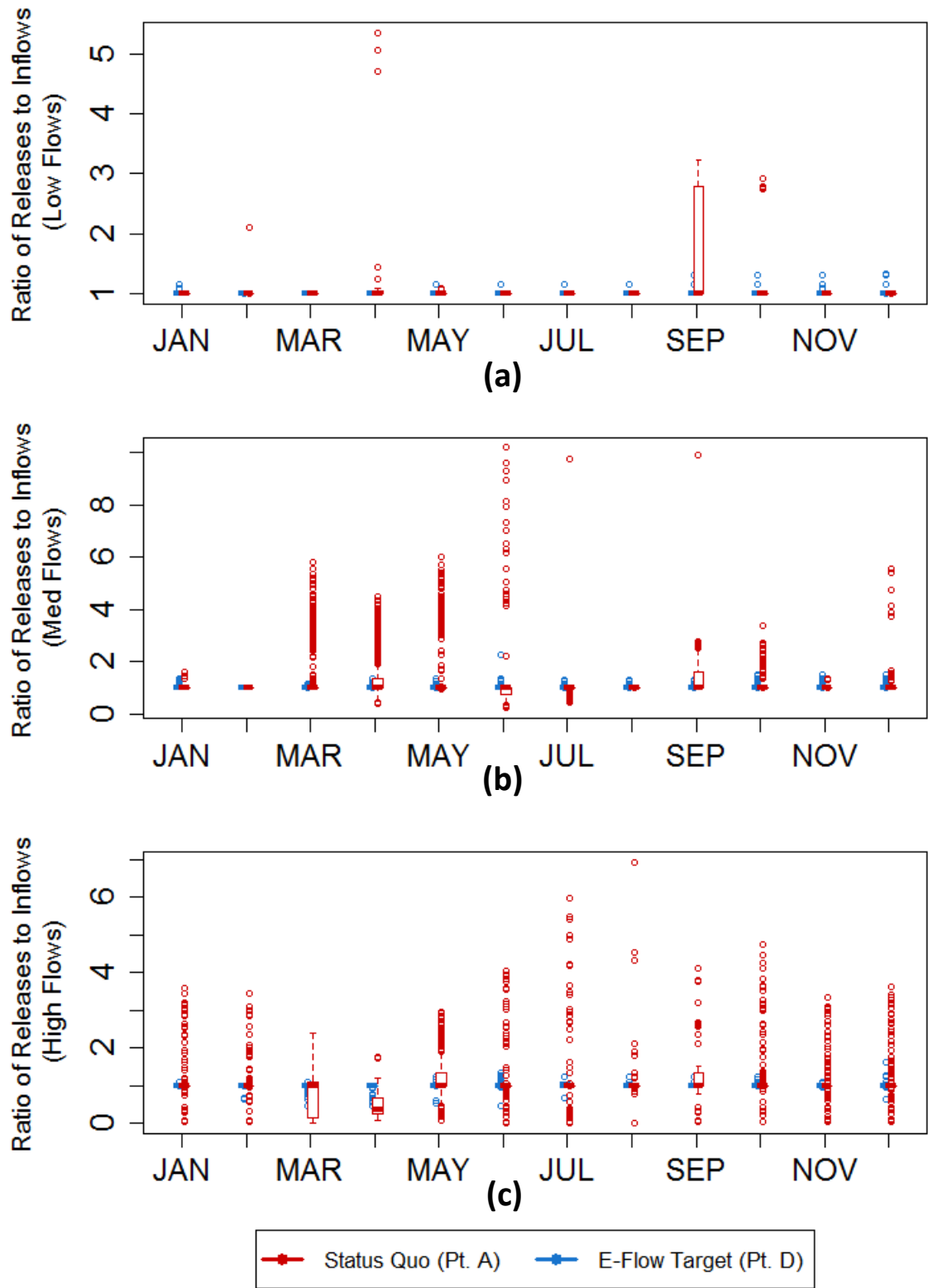


Figure 8: Ratio of releases to inflows at Ball Mountain Dam under the Status Quo and E-Flow Target runs sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

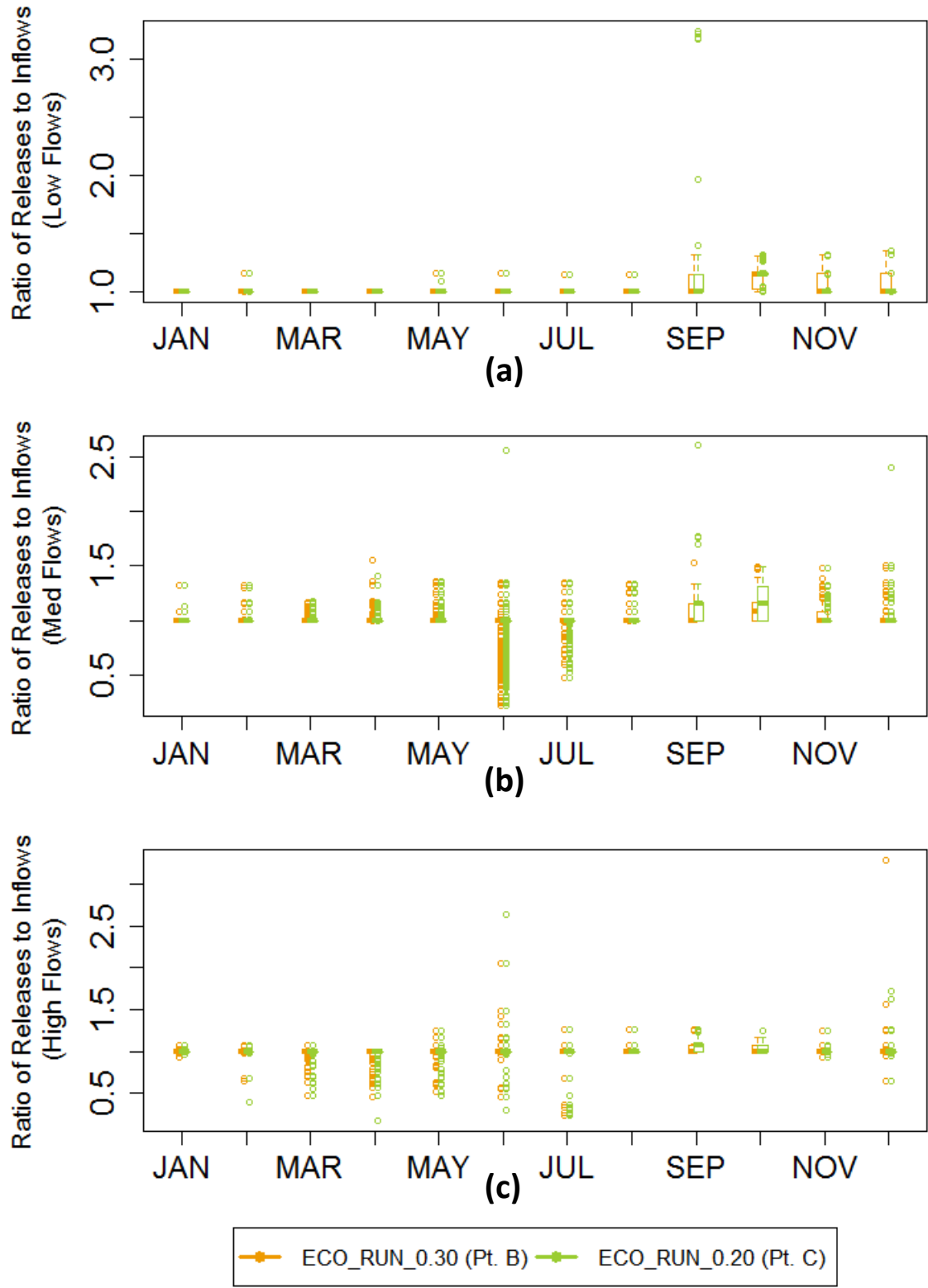


Figure 9: Ratio of releases to inflows at Ball Mountain Dam under the two tradeoff points of interest sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

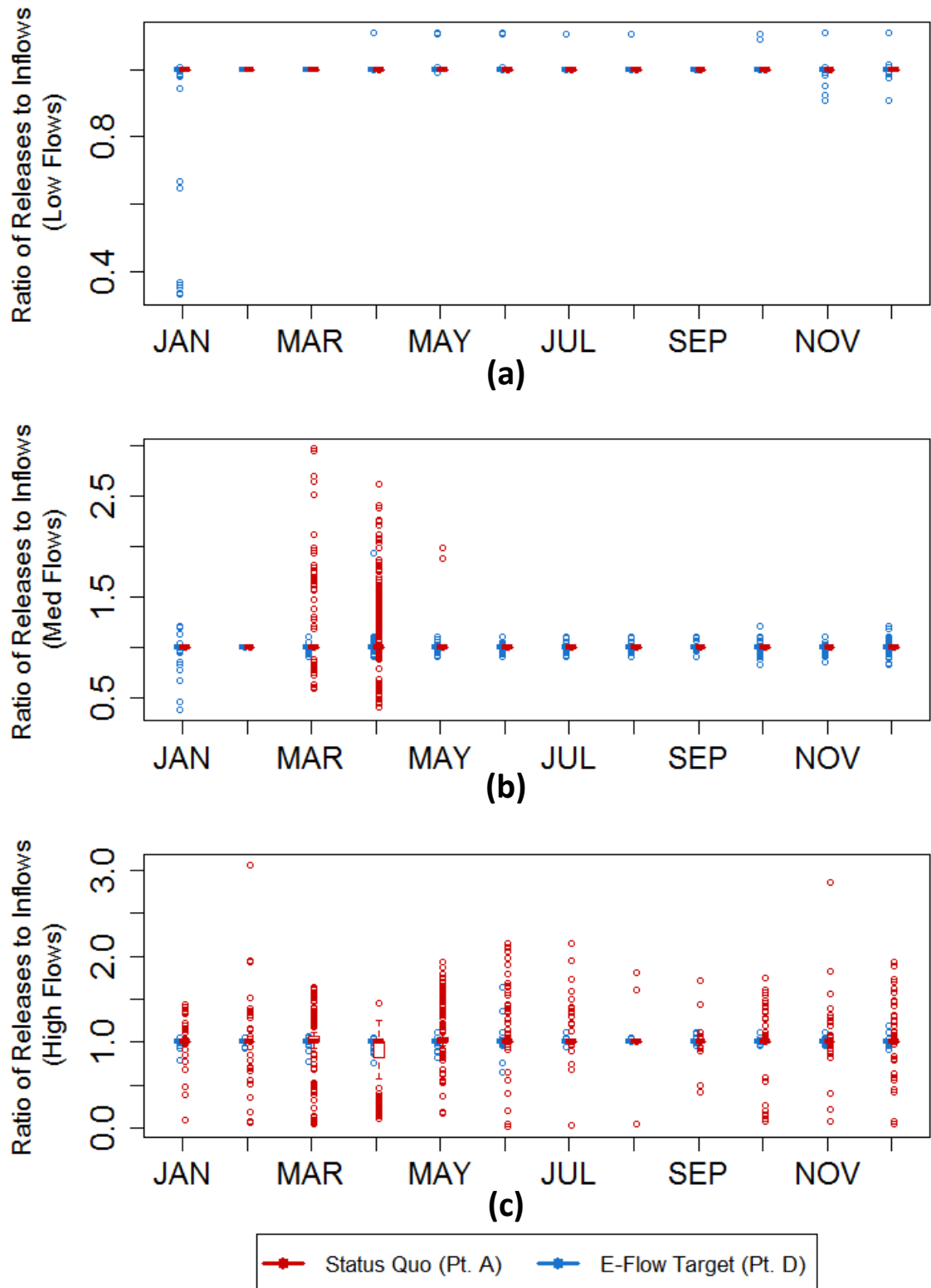


Figure 10: Ratio of releases to inflows at Townshend Dam under the Status Quo and E-Flow Target runs sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

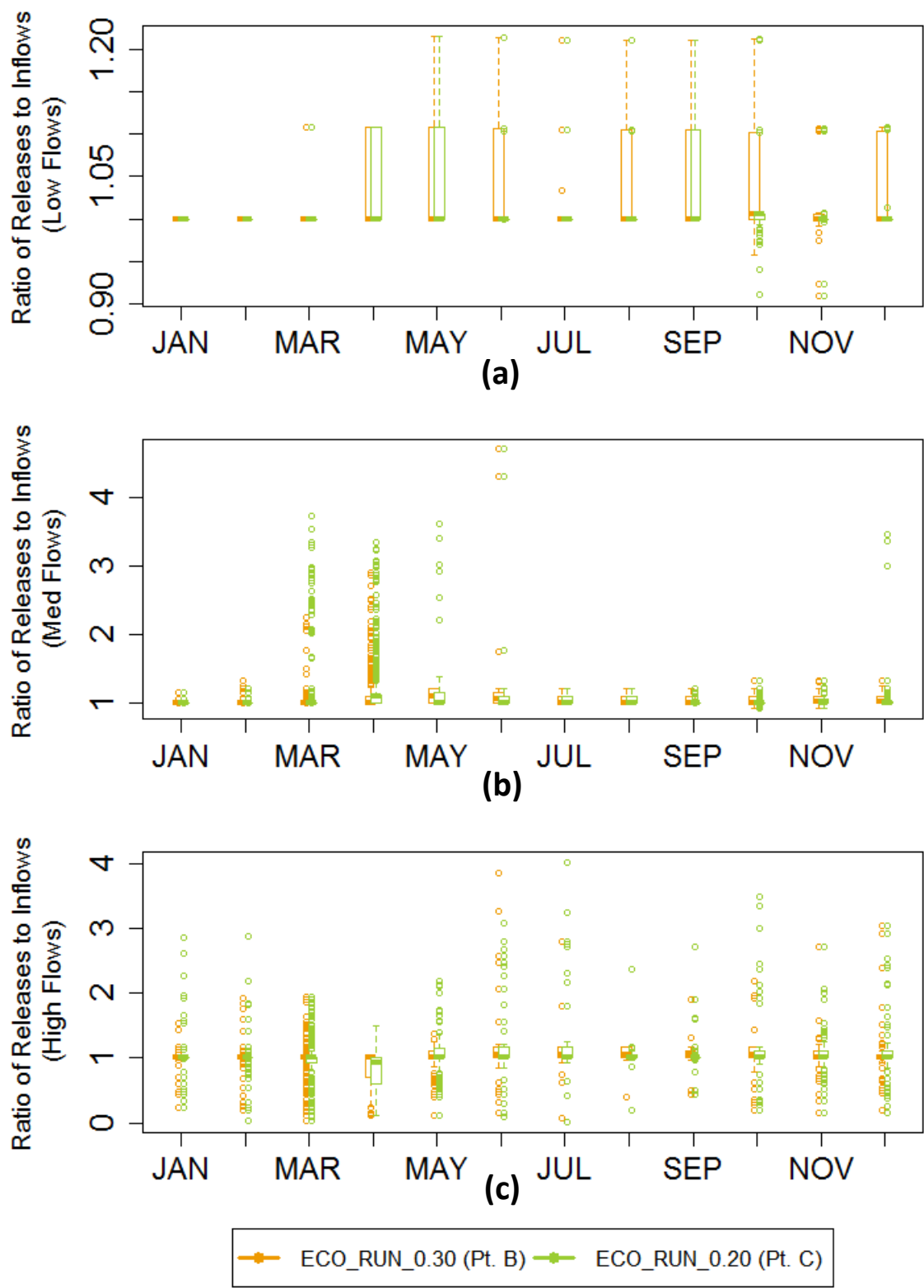


Figure 11: Ratio of releases to inflows at Townshend Dam under the two tradeoff points of interest sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

4.3 Ashuelot Sub-Basin Results

The tradeoff curve for the Ashuelot sub-basin demonstrates that there is some opportunity for ecological penalties to be reduced before significant increases in flooding penalties occur (Figure 12). Points B and C in Figure 12 highlight the “inflection point” are which plausible recommendations can be derived; between these points e-flow penalties are reduced 40-50% while flood penalties increase 3% at point B and 13% at point C.

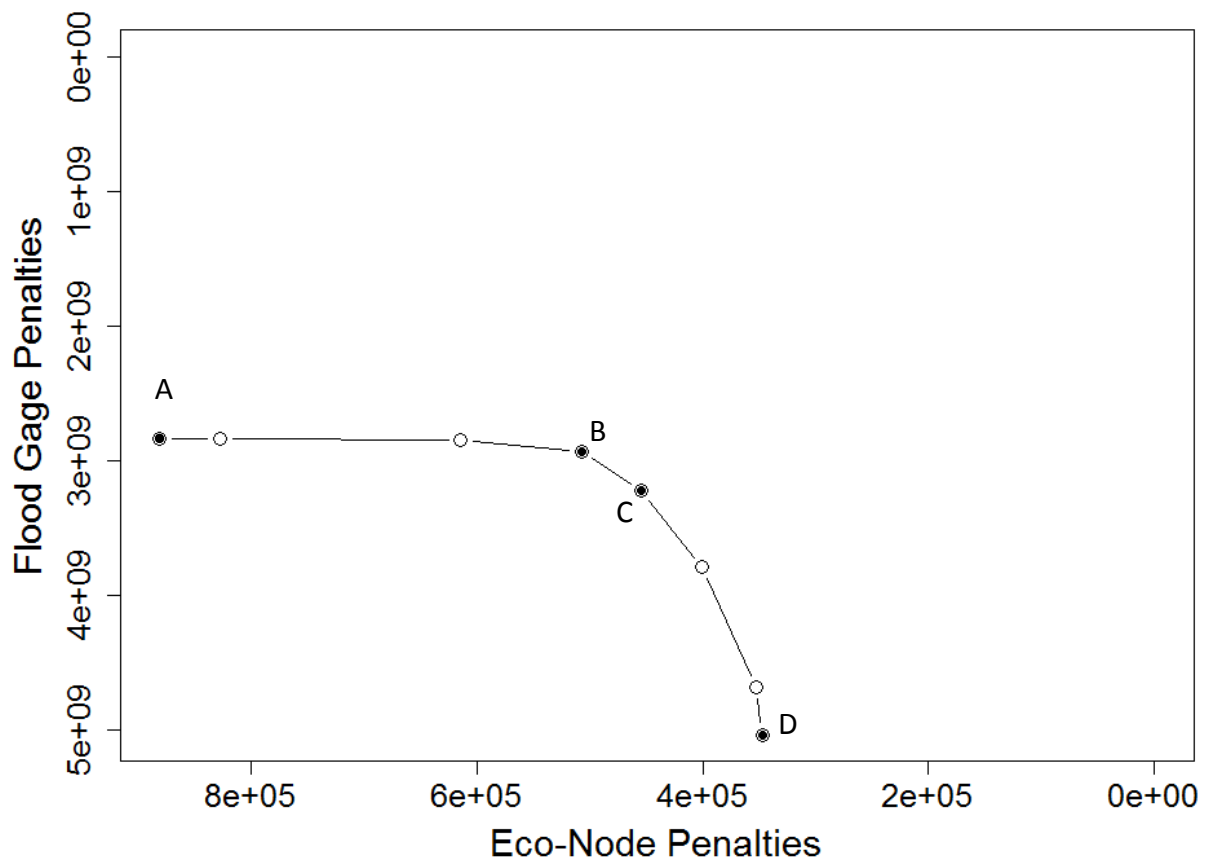


Figure 12: Ashuelot sub-basin tradeoff curve

Deviations from natural flows in the Ashuelot sub-basin are relatively small for both the status quo and environmental flow target runs (Figure 13). Slightly greater deviations are seen at

eco-node 91, where flows are within approximately 4% of natural, compared to eco-node 37 where flows are within approximately 2% of natural. This discrepancy can be attributed to the fact that eco-node 91 is located along the main branch of the Ashuelot river upstream of its confluence with the tributary that Otter Brook Dam is on, so only Surry Mountain can impact flows at this location. In contrast, eco-node 37 is downstream of both reservoirs in the system (Figure 1).

Seasonally, the most significant deviations occur with higher than natural flows in May through July and lower than natural flows in September. The higher summer flows, particularly in the status quo run, can be attributed to releasing captured spring flows as well as the drawdown in Surry Mountain Dam due to a lower summer storage target (Figure 14). The low flows in September appear to occur because of the magnitude of natural flows at this time; average natural streamflow in September is at its minimum so any deviation from natural will be a higher percentage of the flow than at any other time of year.

In general, flows under the e-flow target run are more natural than the status quo flows at both eco-nodes in this basin, though deviations at eco-node 37 are smaller than those incurred at eco-node 91 (Figure 13). Again, this can be attributed to the location of the eco-nodes relative to the reservoirs. Additionally, neither eco-node would be expected to show completely natural flows because the reservoirs, while they are not operating to minimize any particular flood control targets, are still subject to minimum and maximum release constraints which will prevent the model from reaching completely natural flows in extreme droughts or floods.

The average daily storage patterns for the e-flow target and status quo runs are more alike for Otter Brook than Surry Mountain (Figure 14). Though, it should be emphasized that compared to

the capacity of the reservoirs (33,011 acre-feet for Surry Mountain and 18,320 acre-feet for Otter Brook), the changes in storage level between these two runs are a small percentage of total available storage. The status quo run shows storages closer to the target level with increases occurring during periods of high flows. In contrast, the e-flow target run shows storages increasing and decreasing more gradually.

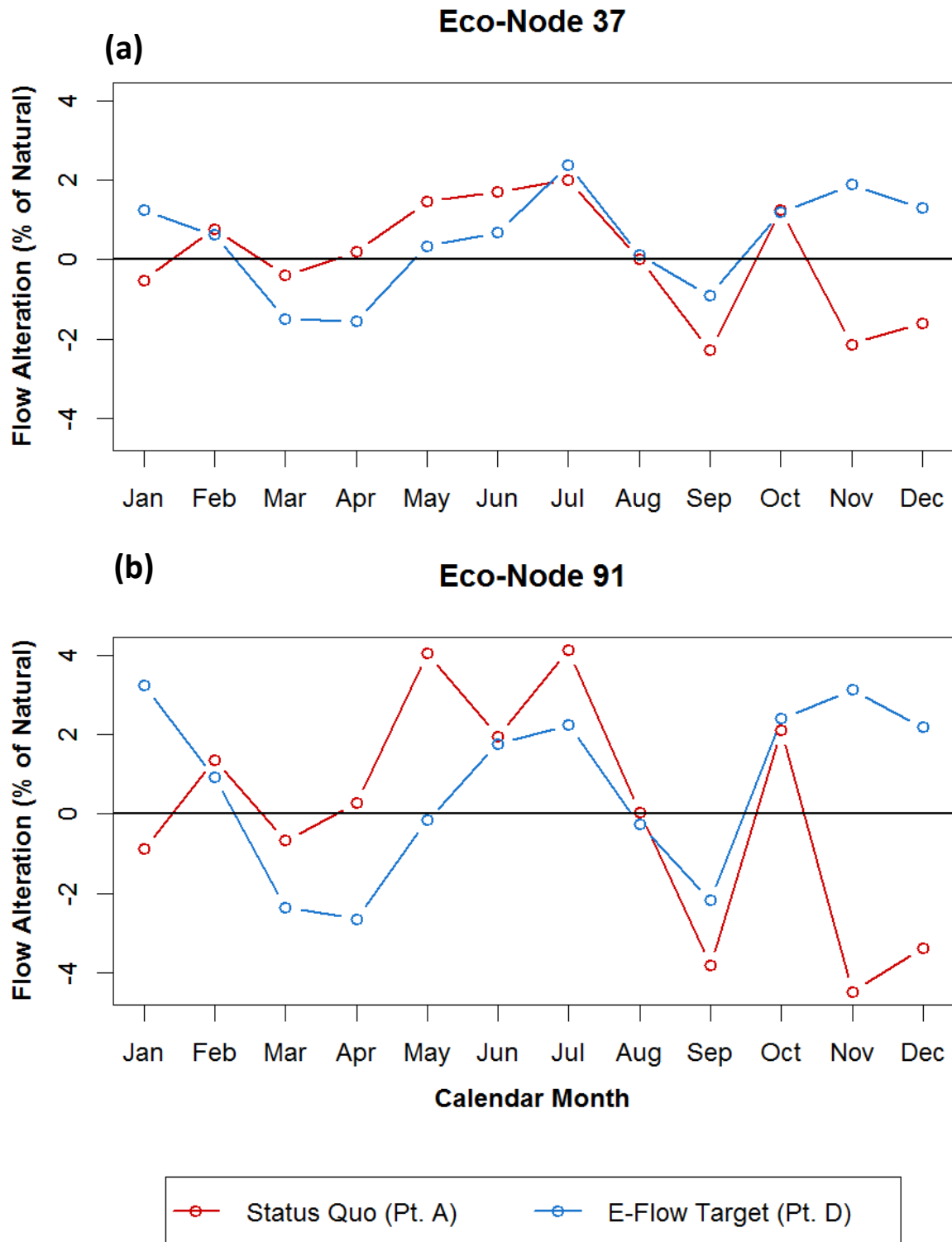


Figure 13: Average monthly flow deviations from natural CRUISE flows at Eco-Nodes (a) 37 and (b) 91 in the Ashuelot Sub-Basin under Status Quo and E-Flow Target runs

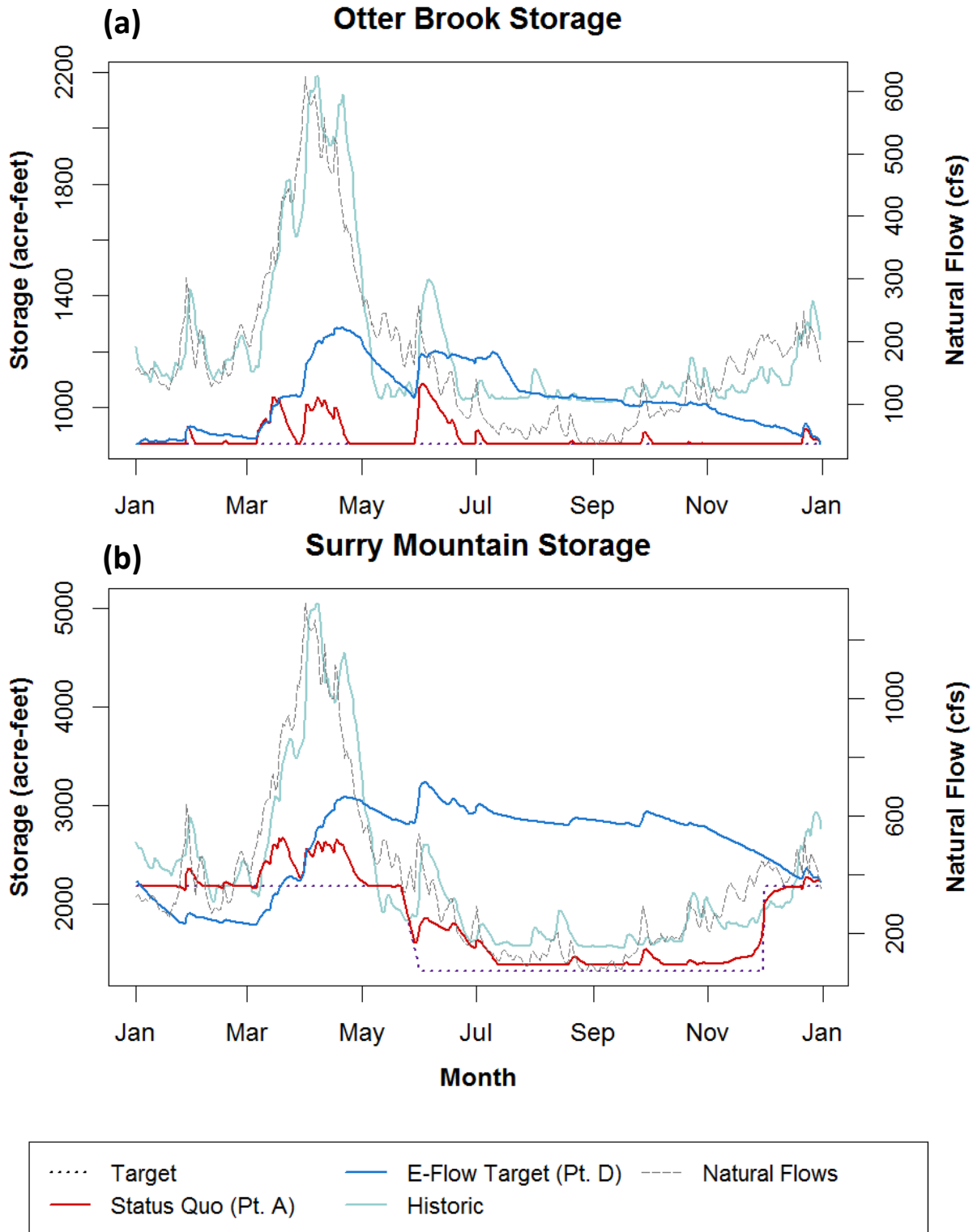


Figure 14: Average daily storage patterns (left axis) in Ashuelot Sub-Basin flood control reservoirs, (a) Otter Brook Dam and (b) Surry Mountain Dam, for USACE-defined Target storage levels, Status Quo and E-Flow Target model runs, and historic storage levels. Right-hand axis presents average daily natural flows.

The flooding penalty in the Ashuelot increases due to more frequent and larger events (Table 7) as maintaining natural flows is more emphasized. There are relatively few flooding events overall with a consistent median flood magnitude for most model runs. When moving from “ECO_RUN_0.30” to “ECO_RUN_0.20” there are the same number of flood events but the maximum magnitude increases by 2% resulting in 10% more flood penalties. The model outputs indicate that flooding is an infrequent event at the Hinsdale flood gage under historic hydrology. Any increase in flooding events, or their magnitude, while having a significant impact on the modeled flood penalty, likely would not cause a similar increase in physical damage.

Table 7: Number of and average magnitude of flow events above the flooding threshold (9,360 cfs) at the Hinsdale gage in the Ashuelot sub-basin over the 43 years of model runs

Model Run Name	Occurrences	Maximum Flood Magnitude	Maximum Distributed Flood Magnitude	Median Flood Magnitude	Occurrences within 10% of Max. Magnitude
Status Quo (Pt. A)	4	12,195	11,346	10,760	2
ECO_RUN_0.90	4	12,195	11,346	10,760	2
ECO_RUN_0.50	4	12,195	11,346	10,760	2
ECO_RUN_0.30 (Pt. B)	4	12,355	11,346	10,760	2
ECO_RUN_0.20 (Pt. C)	4	12,645	11,346	10,760	1
ECO_RUN_0.10	5	12,645	11,778	10,180	2
ECO_RUN_0.01	5	13,095	12,504	10,640	2
E-Flow Target (Pt. D)	7	13,095	12,646	10,240	2

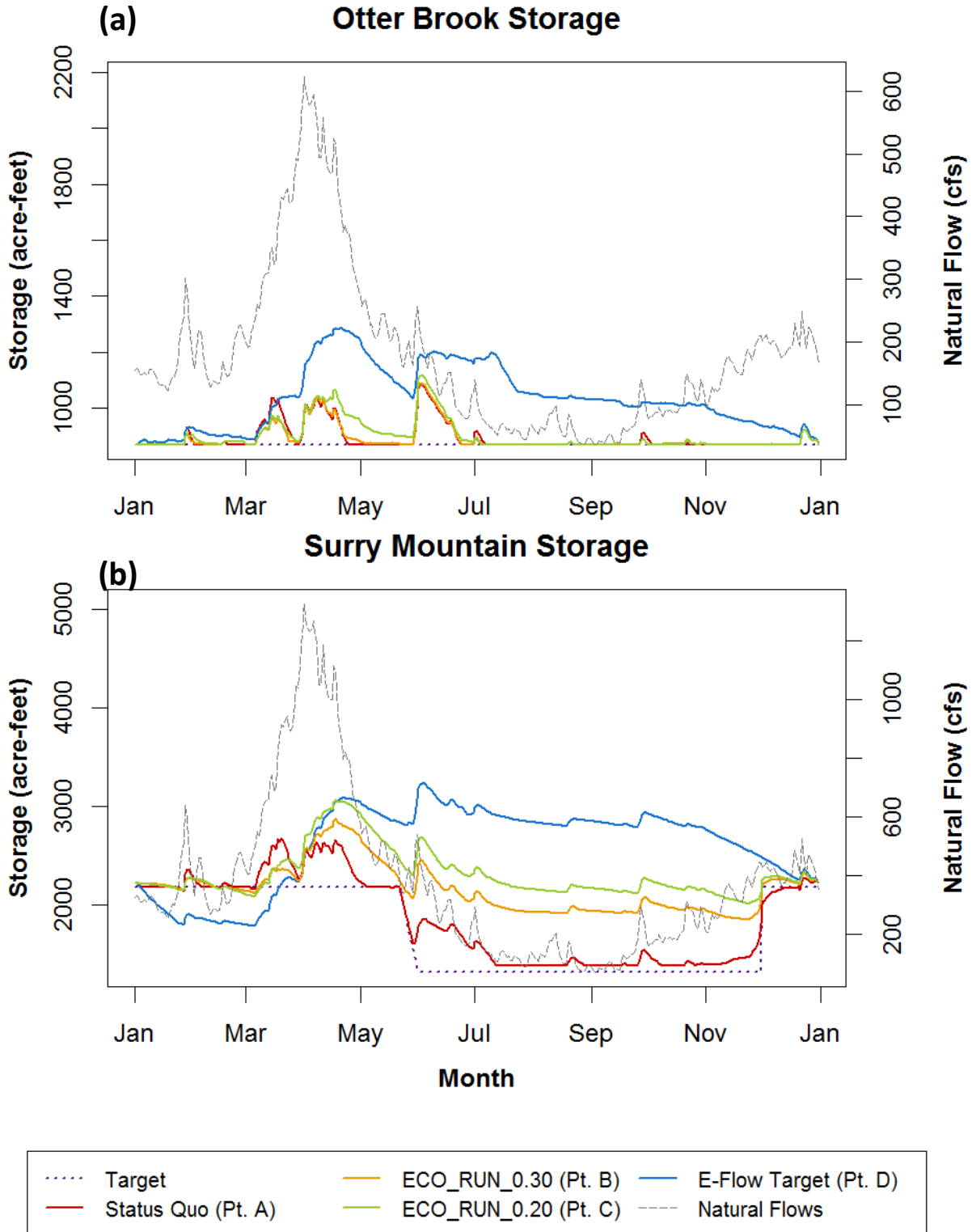


Figure 15: Average daily storage patterns (left axis) in Ashuelot Sub-Basin flood control reservoirs, (a) Otter Brook Dam and (b) Surry Mountain Dam, for the four modeled tradeoff curve points of interest as well as USACE-defined target storage levels. Right-hand axis presents average daily natural flows.

4.4 Ashuelot Sub-Basin Recommendations

Because reservoir storage in the Ashuelot basin only modestly impacts natural flows, there are fewer opportunities for re-operation than in the West basin. However, some gains can be made without sacrificing flood protection. The summer storage target at Surry Mountain should be increased by 1,000 acre-feet while Otter Brook's year-round target should be increased approximately 1,000 acre-feet (Figure 14 and Figure 15). Additionally, drawdown process should be more gradual.

To provide more specific recommendations, the monthly ratios of releases to inflows for each reservoir were examined. Figure 17 and Figure 18 present the ratio of releases to inflows for Otter Brook Dam under four model runs of interest (as identified in Figure 12) and Figure 19 through Figure 20 present the same metric for Surry Mountain Dam (additional figures showing greater resolution can be found in Section 7). Inspection of this metric lead to the recommendations in Table 8 which are the recommended release rules based on inflow levels (see Section 4.2 for explanation of table columns).

Table 8: Monthly recommended releases for Ashuelot reservoirs under three flow regimes. Low Flows are defined as the lowest 15% of reservoir inflows, Med. Flows are defined as the middle 70% of reservoir inflows, and High Flows are defined as the highest 15% of reservoir inflows. Values shown are the allowable percent deviation from inflows.

Month	Surry Mountain Dam						Otter Brook Dam					
	Low Flow		Med Flow		High Flow		Low Flow		Med Flow		High Flow	
	- %	+ %	- %	+ %	- %	+ %	- %	+ %	- %	+ %	- %	+ %
March	0	10	0	50	40	30	0	0	20	100	50	60
April	0	10	0	30	40	20	0	25	0	100	40	50
May	0	40	0	50	30	25	0	25	0	30	25	40
June	0	20	15	500	50	125	0	30	10	1000	20	125
July	0	20	0	45	10	100	0	0	0	5	10	50
August	0	30	0	45	20	75	0	0	0	0	10	10
Sept	0	20	0	40	40	30	0	0	0	5	20	20
October	0	40	0	60	25	40	0	0	10	30	20	40
November	0	40	50	60	50	10	0	0	10	30	0	10
December	0	0	60	40	70	50	0	0	10	10	40	75
January	0	10	0	40	40	10	0	0	10	0	30	40
February	0	10	0	30	20	10	0	0	15	30	30	40

From Table 8 some general trends emerge. During low flow events, both reservoirs should release at least their inflows, with Surry Mountain releasing more if needed to draw down the reservoir. June is an outlier for the moderate flow recommendations where releases that are much higher than natural inflows may be required; a spike in storage levels can be seen across all storage plots which can explain this anomaly. In general, however, during moderate flows both reservoirs should release higher than natural flows. Additionally, during medium inflows, Otter Brook should more consistently skim inflows than Surry Mountain but at lower levels. For high flows, the reservoirs require greater flexibility in order to capture and release water in a regulated fashion to prevent flooding downstream. Again, these releases should be made as gradually as possible with only the most extreme events causing operations to reach these limits of recommended operation.

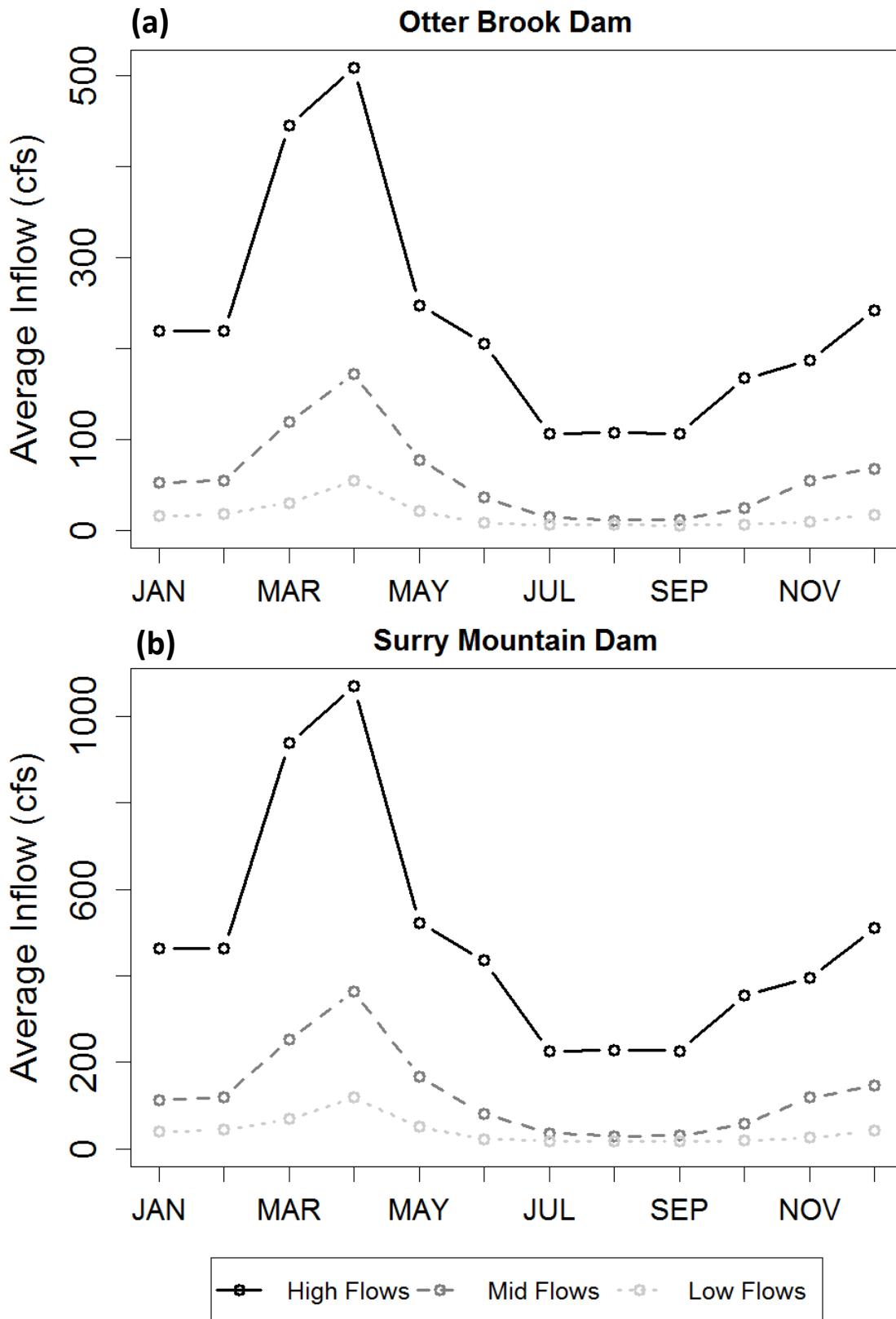


Figure 16: Average monthly reservoir inflows ranked by lowest 15%, middle 70% and highest 15% for (a) Otter Brook Dam and (b) Surry Mountain Dam

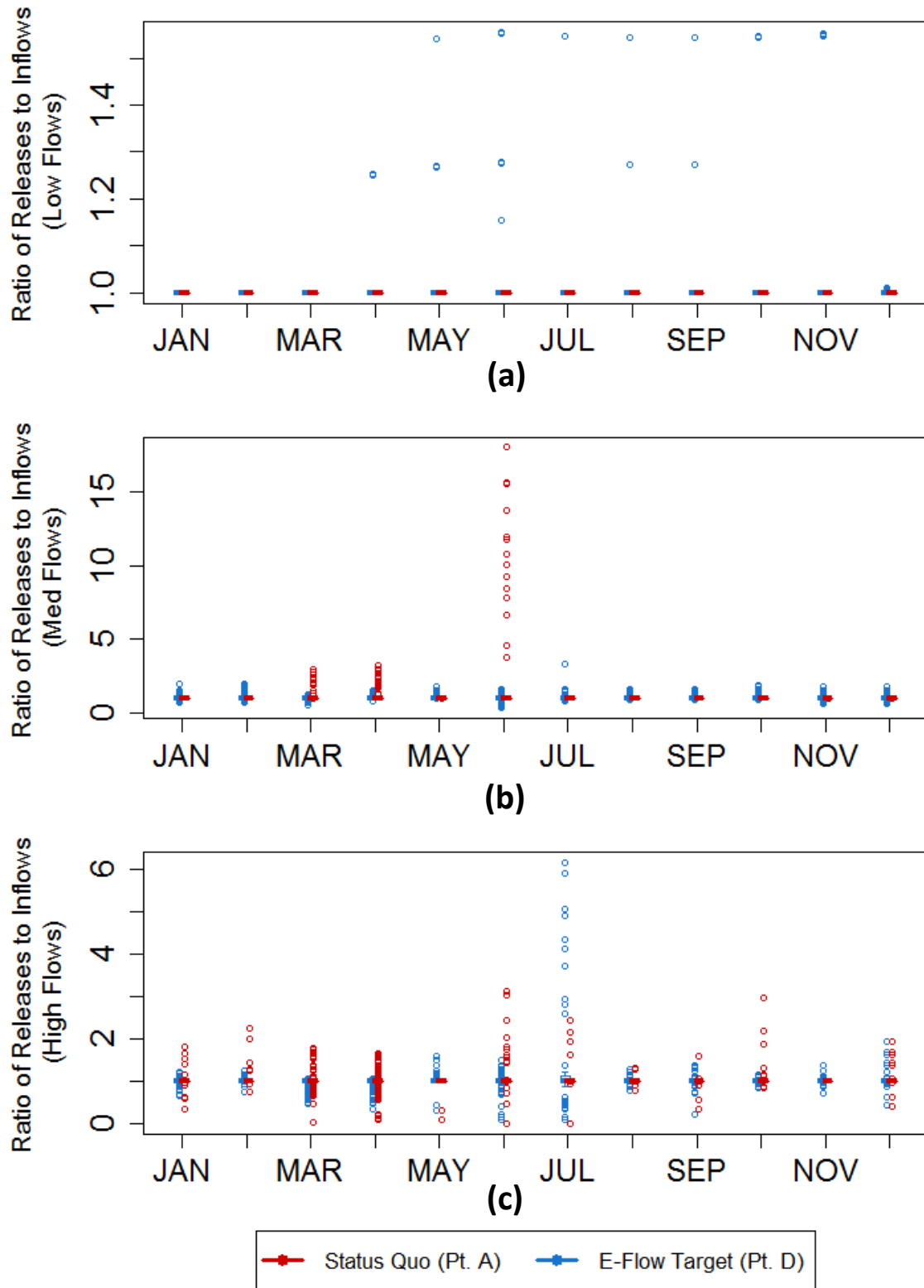
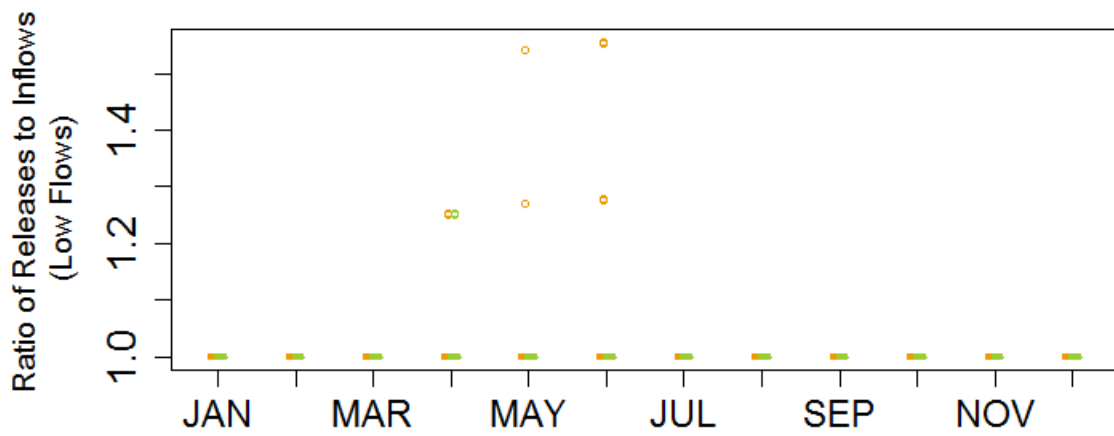
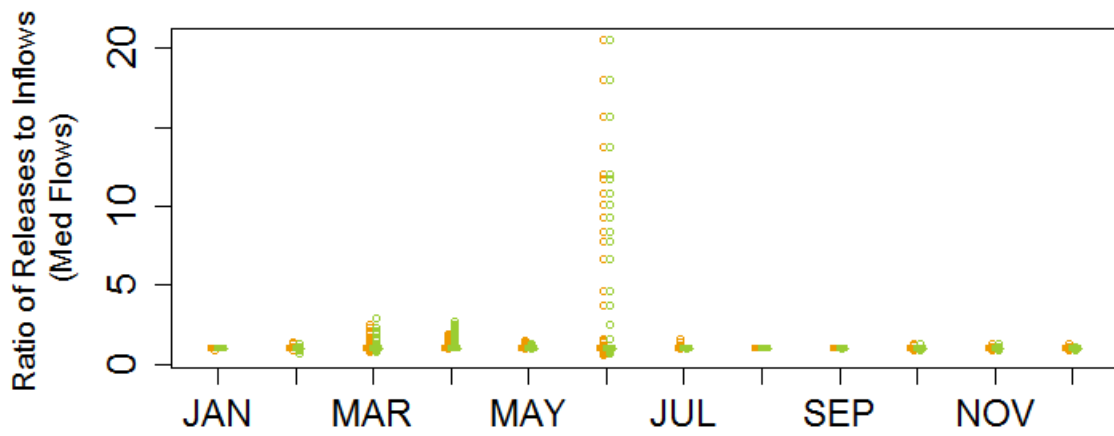


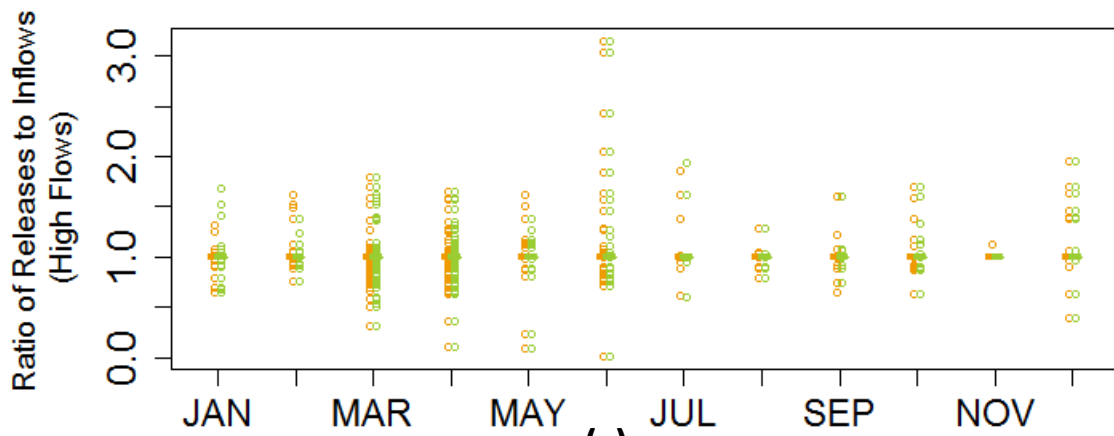
Figure 17: Ratio of releases to inflows at Otter Brook Dam under the Status Quo and E-Flow Target runs sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%



(a)



(b)



(c)

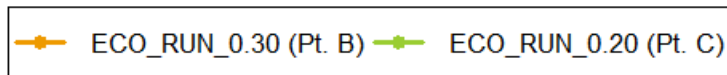


Figure 18: Ratio of releases to inflows at Otter Brook Dam under the two tradeoff points of interest sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

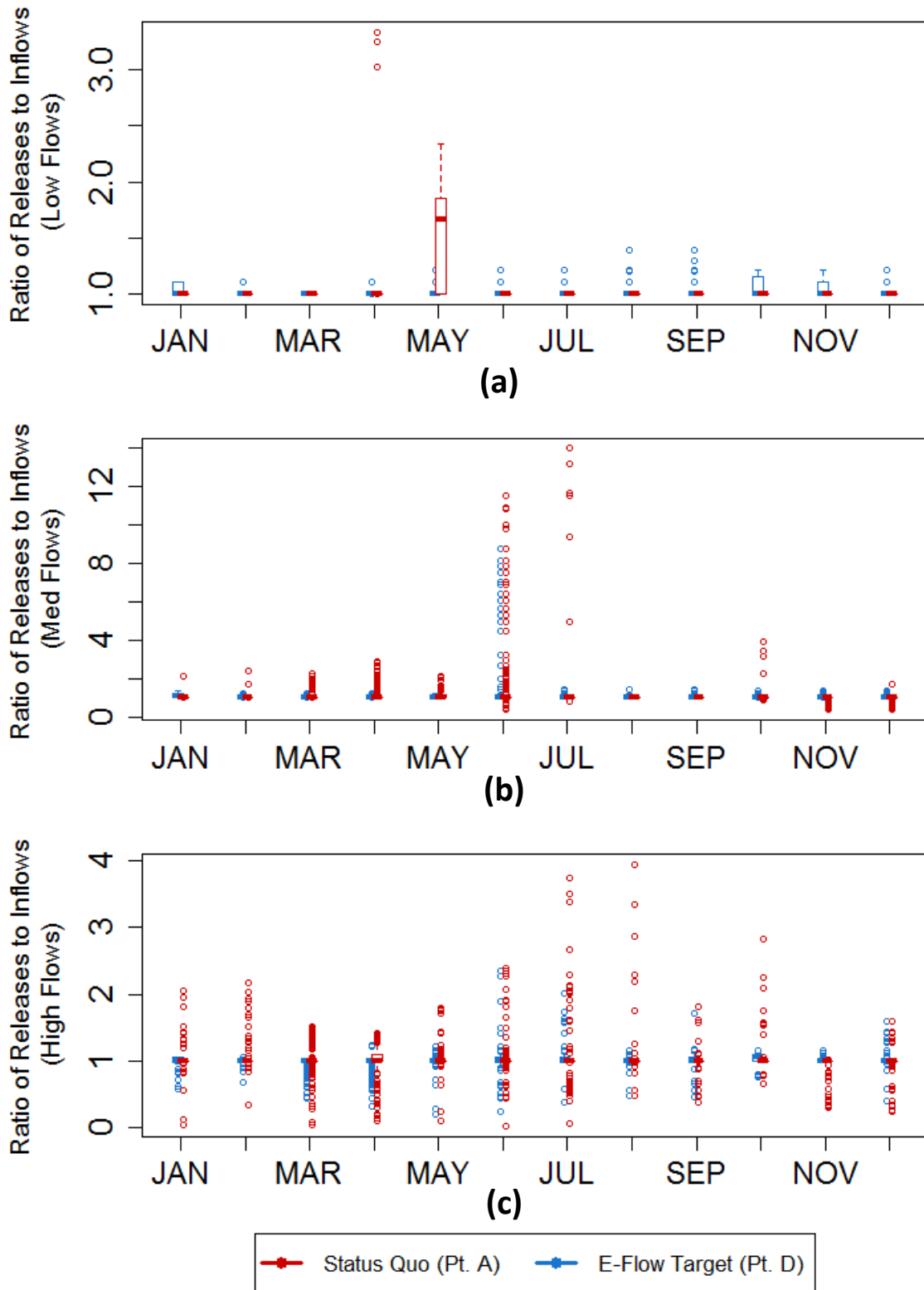


Figure 19: Ratio of releases to inflows at Surry Mountain under the Status Quo and E-Flow Target runs sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

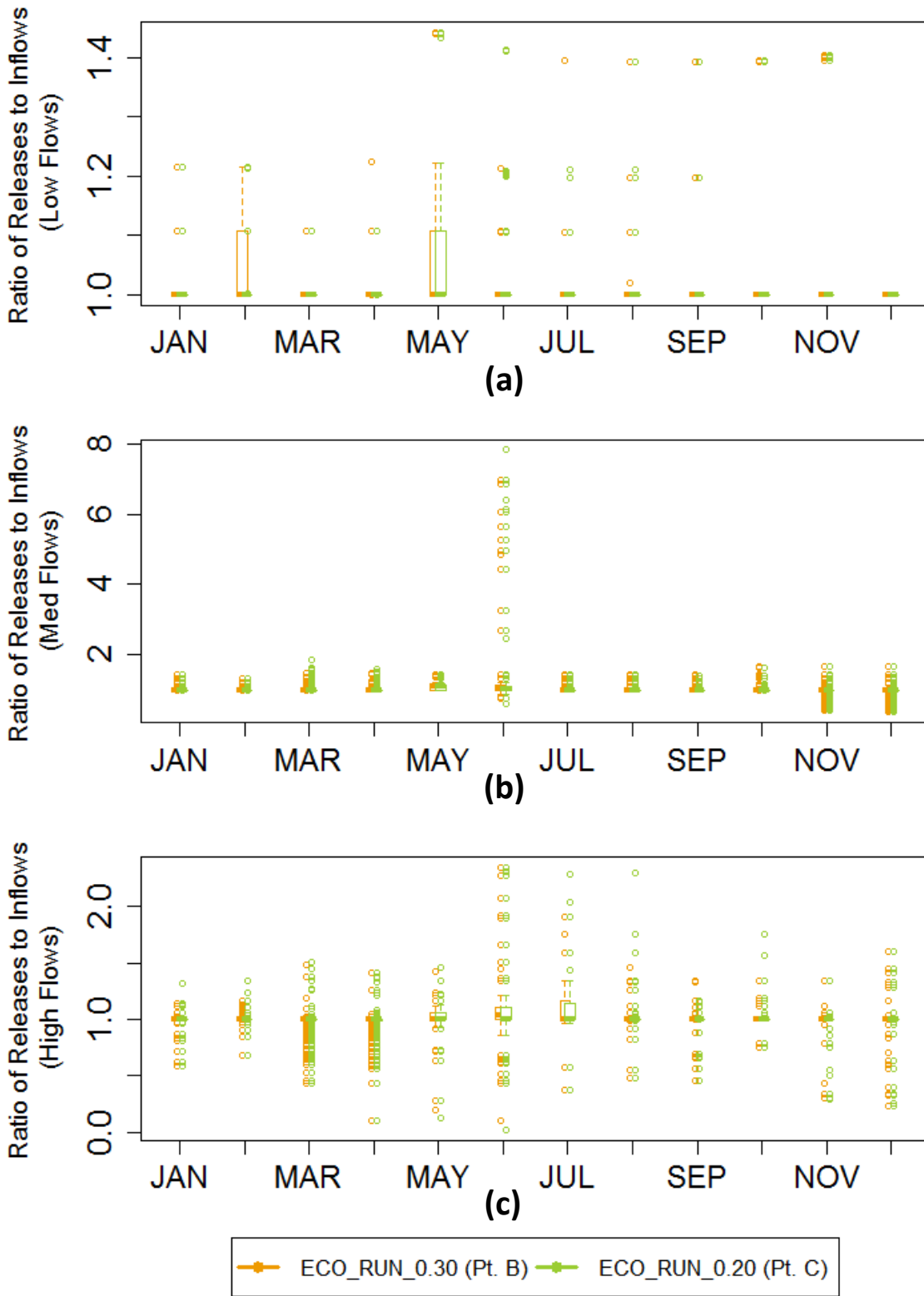


Figure 20: Ratio of releases to inflows at Surry Mountain under the two tradeoff points of interest sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

5 CONCLUSIONS AND FUTURE WORK

The Connecticut River Optimization Modeling Environment (CROME) was successfully used to investigate the tradeoffs between minimizing flooding events while maximizing natural flows by applying it to two case study locations within the Connecticut River Basin (CRB). The optimization model framework provided an opportunity to evaluate various operational choices to identify potential trade-offs between these two objective function values. The model output was adequately detailed both spatially and temporally to allow for general conclusions to be reached, as well as specific recommendations to be made for potential changes in operations.

Both case studies demonstrated that there is an opportunity to improve natural flows downstream of flood control reservoirs without significantly increasing flooding instances. On average, and even under higher flow scenarios, the flood control reservoirs are not using their capacity. This indicates that under historic hydrology, most flows can pass through the reservoir without damaging property downstream. Furthermore, if more high-flow, but not flood-level, events were allowed to pass, there would be ample capacity to hold back more extreme events.

While flows mimicking a natural basin are most beneficial for species and ecosystems, it is recognized that a completely natural flow regime cannot be returned while maintaining the benefits associated with flood control infrastructure. In neither sub-basin were completely natural flows achieved even in the e-flow target scenario because of the physical constraints of the reservoirs. However, the importance of the e-flow paradigm is that riverine ecosystems have both an adequate volume of water as well as sufficient variability to best imitate a natural, unimpacted system. This study demonstrated that the optimization model framework, using a dynamic environmental flow target structure, can be utilized to find operational plans to achieve that goal.

By comparing the ratio of reservoir releases to reservoir inflows across various reservoir inflow volumes, seasons and model runs, a set of operational recommendations was created. To achieve more natural flows, releases should be equal to inflows whenever possible, but particularly in low flow times. High flow scenarios require more operational flexibility to prevent downstream flooding, but this flexibility should only be used when flows are reaching damaging magnitudes. In more average or moderate inflow times, some operational flexibility is recommended, but to a smaller degree of what is needed during peak flow times.

While there were similar overall findings in the two case studies in this paper, there were some unique differences as well. The ratio of available storage to average basin flows, as well as the spatial distribution of reservoirs affects the ability of reservoirs to impact streamflow. Deviations from natural flows at eco-nodes in the Ashuelot sub-basin are smaller than in the West sub-basin; this indicates that the Ashuelot reservoirs have less of an impact on the flows in their basin than those in the West. There are a few possible reasons for this. First, Otter Brook dam is located on a tributary to the Ashuelot River meaning it has control over a smaller percentage of flows passing through the basin, whereas in the West basin, both reservoirs are located on the main stem of the river. In addition, the ratio of flood control storage to average annual flow is just over 10% in the Ashuelot compared to 13.5% in the West. These two factors (location of reservoirs relative to locations of interest and ratio of flood control storage to average annual flow) could be used to screen basins in order to determine those that have the most room for improvement and should be investigated further.

While this optimization model output provided suggested recommendations for operations, there is still opportunity to refine these suggestions. As part of the existing study with The Nature Conservancy (TNC), the U.S. Army Corps of Engineers (USACE) has built a simulation

model of the CRB system; this simulation model will be used to test the recommendations provided in this paper. This will become an iterative process using both the simulation and optimization models to identify realistic and useful operational changes to the system.

It is important to adjust CROME's model parameters as more information becomes available. In the series of workshops and webinars used to develop the dynamic e-flow targets used in CROME, the aquatic biologist and scientists requested information on the sensitivity of model output to changes in the allowable bounds they recommended. Using a linear programming (LP) framework affords the opportunity to perform sensitivity analysis on these bounds. Such an analysis would be able to identify the species, flow decile, and month of year that is constraining the model results most significantly. This level of specificity could aid stakeholders in honing their research to justify the existing bounds or allow for more operational flexibility.

The analysis of flood control benefits would be more useful if risk was incorporated into the framework. Flood damages are exponential and this model simplifies the correlation between the size of flood and the penalties incurred. The model could be improved if an accurate model of potential damages was incorporated into the framework. Further, the current framework of this model applies an optimization model which has perfect foresight of system inflows, which is not a good analogue of the reality which operators face.

As the hydrologic impacts of climate change become more important for water resource managers to understand, existing tools should be adapted for this purpose. CROME has the flexibility to perform analyses with various hydrologic inputs; in a previous study (Polebitski, O'Neil, & Palmer, 2012) climate altered streamflow for the CRB under 112 different climate

futures were developed. These should be analyzed in CROME to determine how operational rules should be adjusted in the future.

Returning rivers to a more natural state by providing sufficient flow, as well as variability, promotes healthy ecosystems. It is well documented that man-made infrastructure can affect both flow volume as well as variability. Flood control reservoirs provide significant societal benefit, but can reduce the occurrence of high flow events that are critical for floodplain health and can introduce artificial pulses when making large reservoir releases. For the West and Ashuelot Rivers in the CRB, there is opportunity to achieve more natural flows without significantly increasing flooding events.

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7 APPENDIX A: Supplemental figures and tables

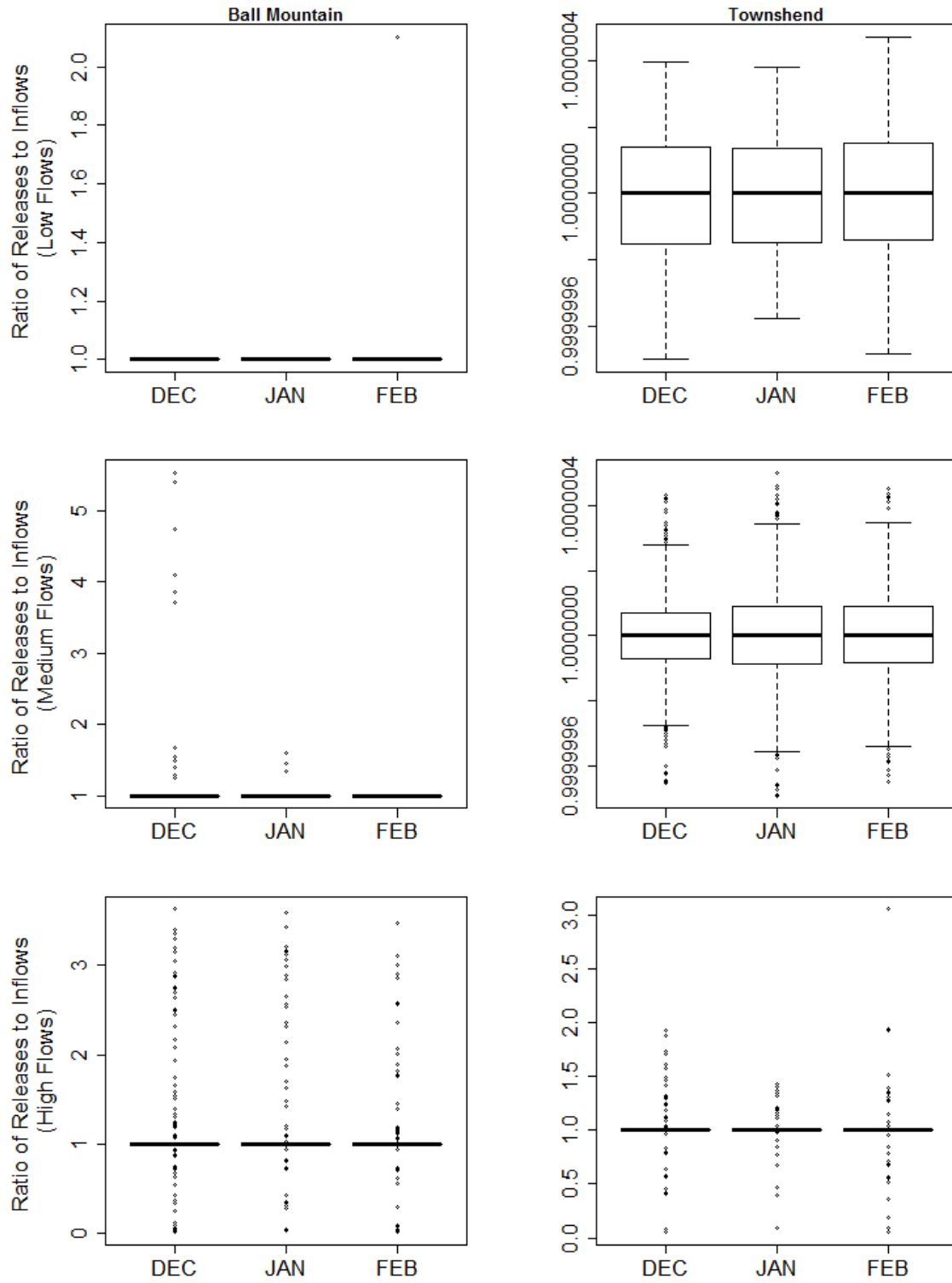


Figure A 1: Ratio of releases to inflows in West Sub-Basin reservoirs under the status quo-run, for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

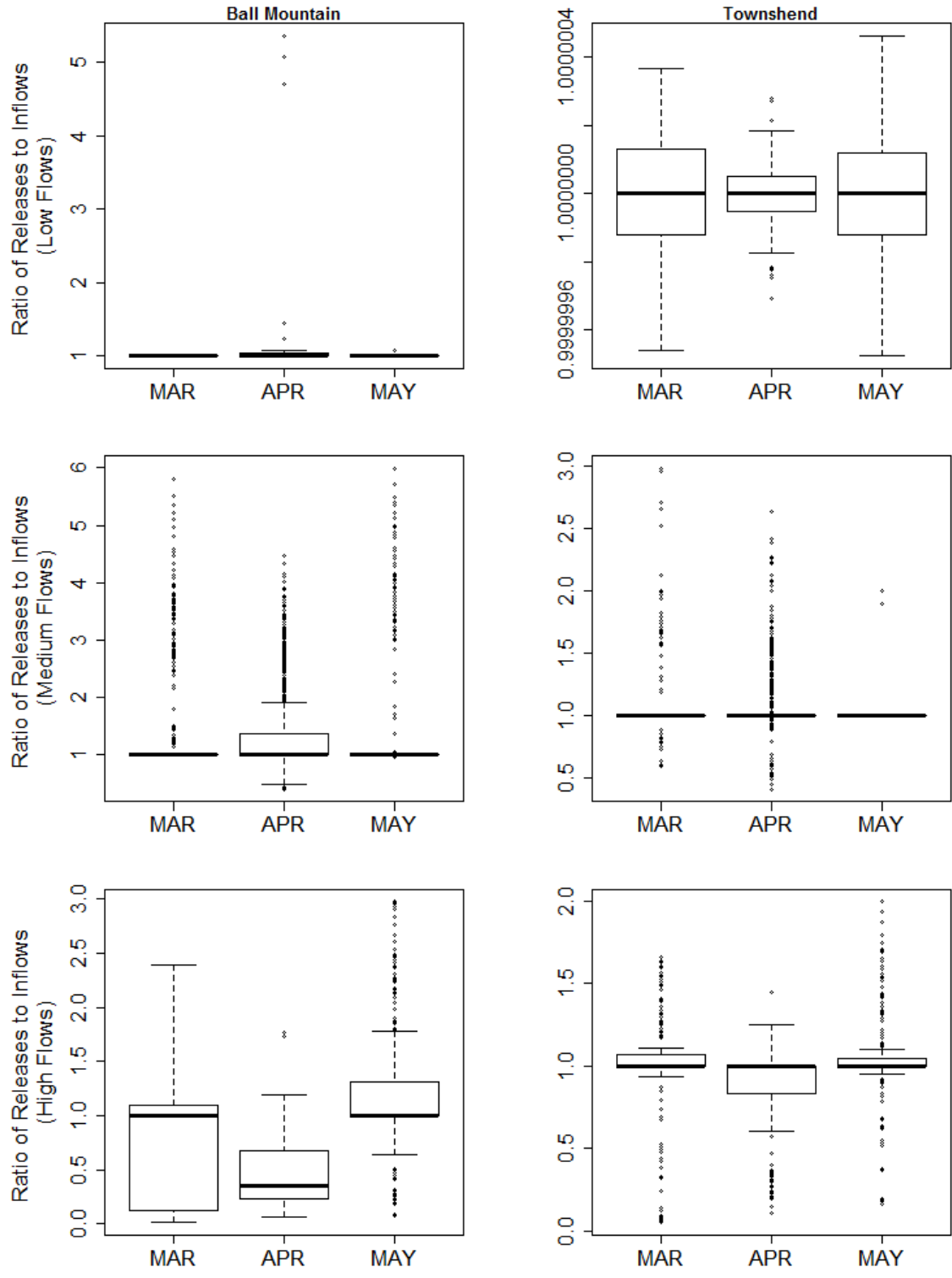


Figure A 2: Ratio of releases to inflows in West Sub-Basin reservoirs under the status quo-run, for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

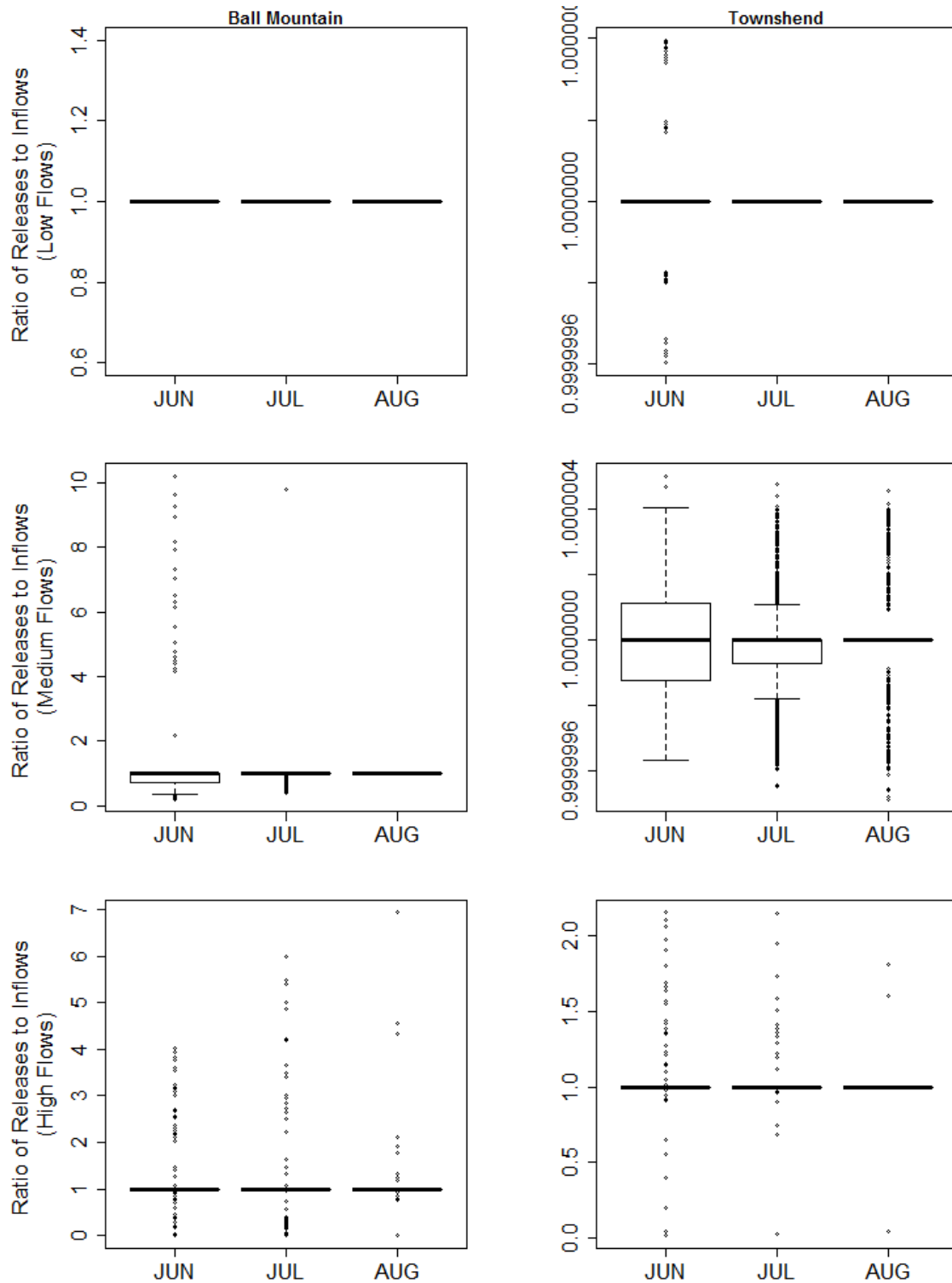


Figure A 3: Ratio of releases to inflows in West Sub-Basin reservoirs under the status quo-run, for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

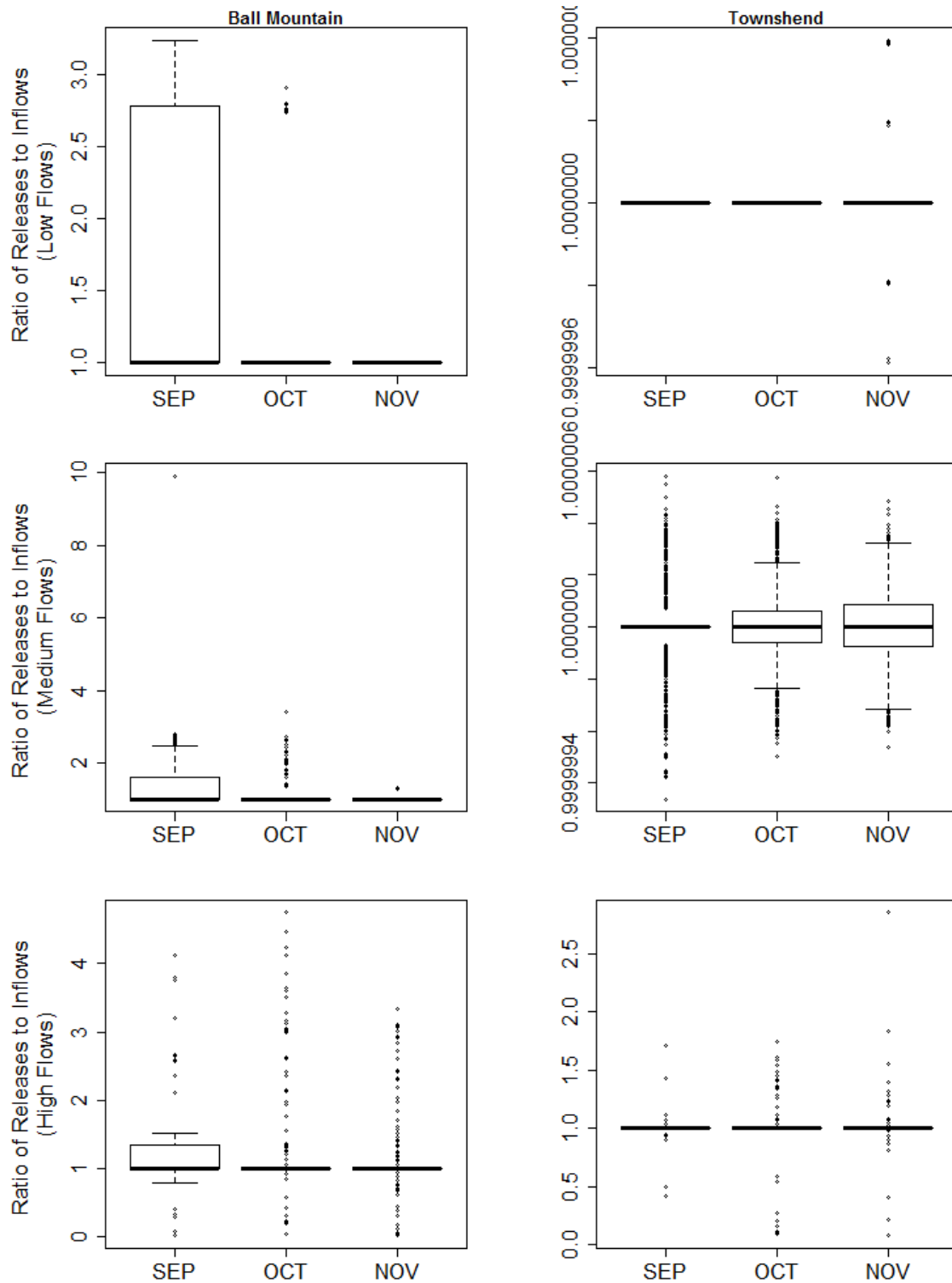


Figure A 4: Ratio of releases to inflows in West Sub-Basin reservoirs under the status quo-run, for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

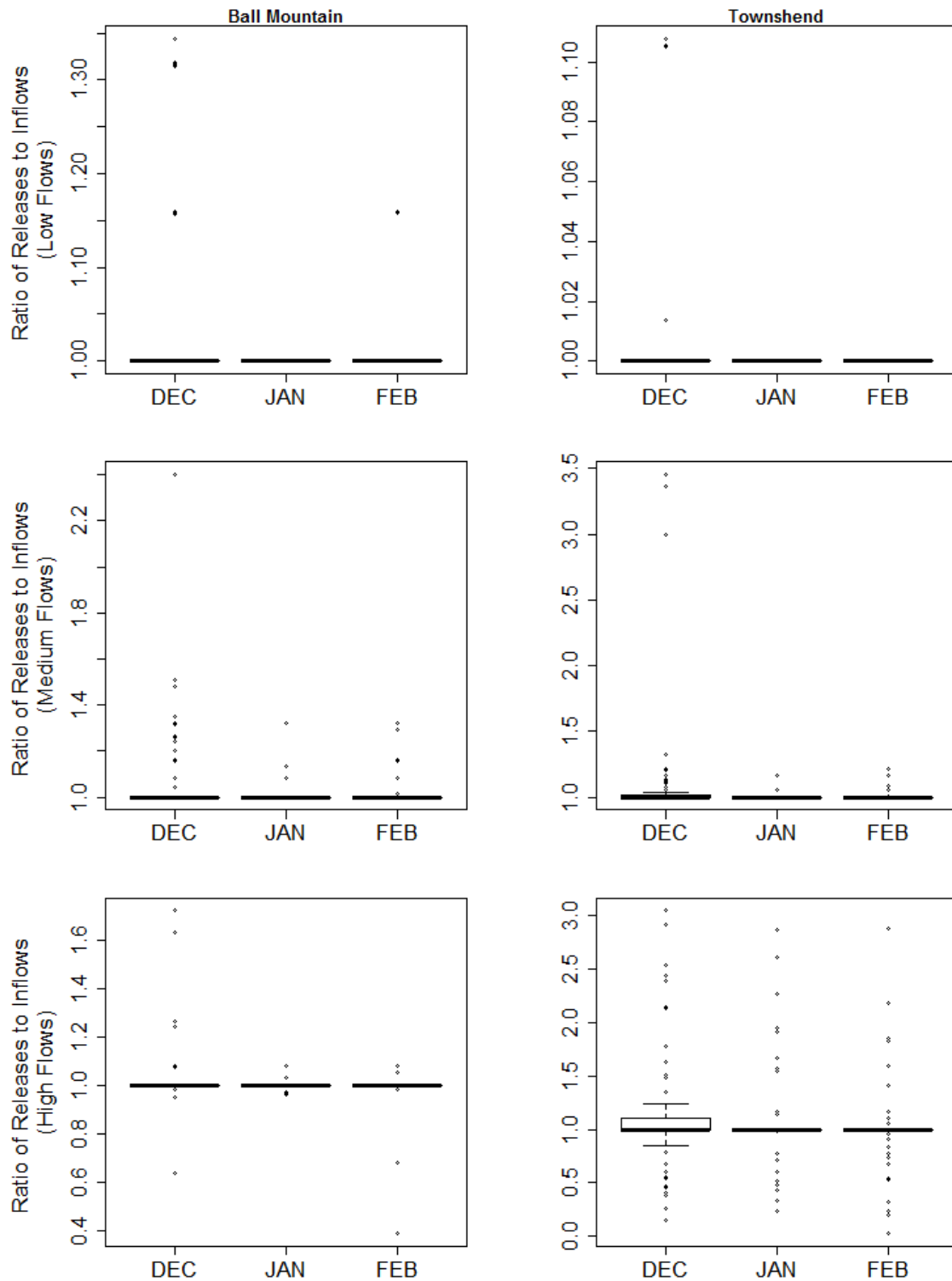


Figure A 5: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.30” run, for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

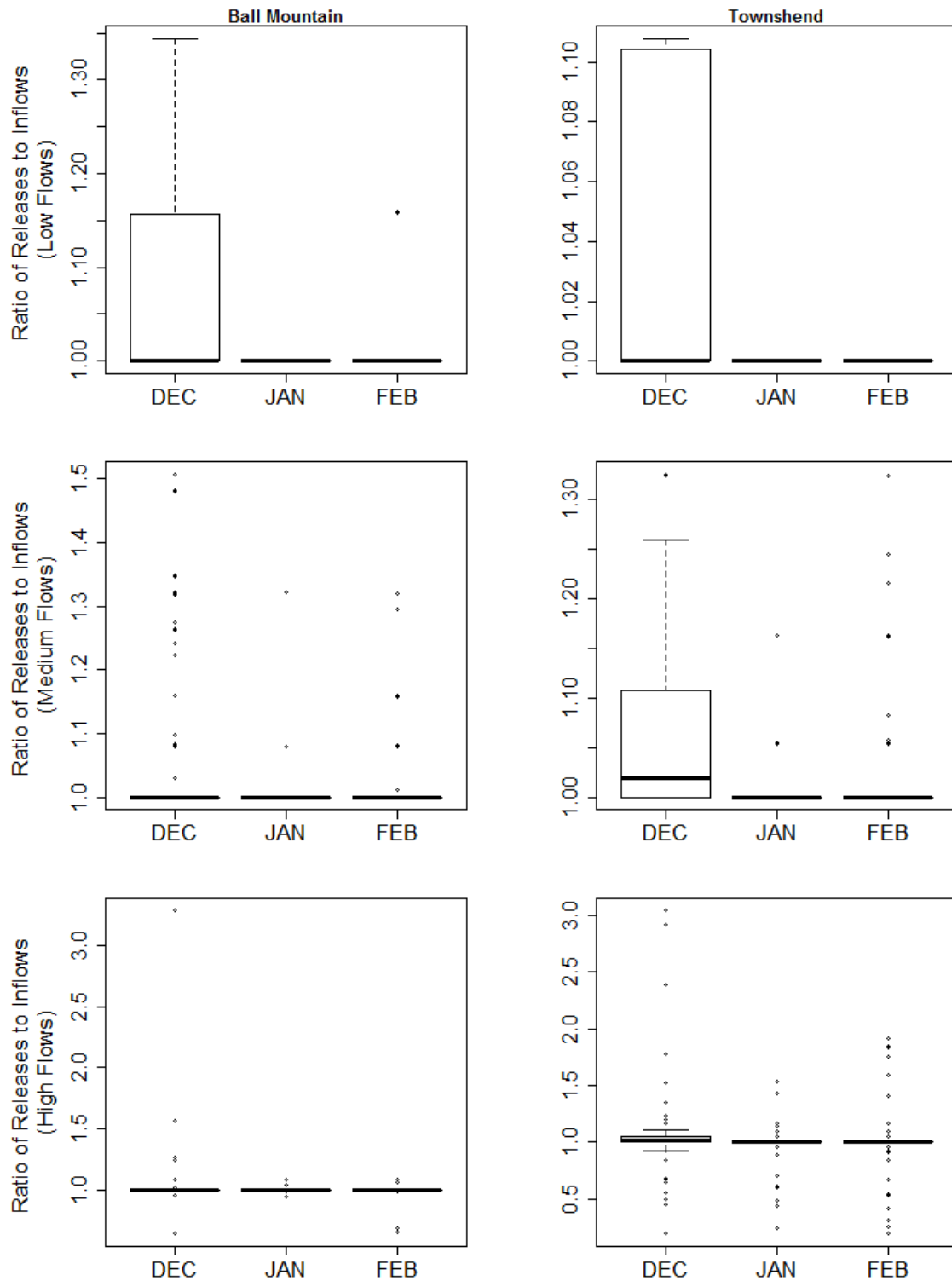


Figure A 6: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.20” run, for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

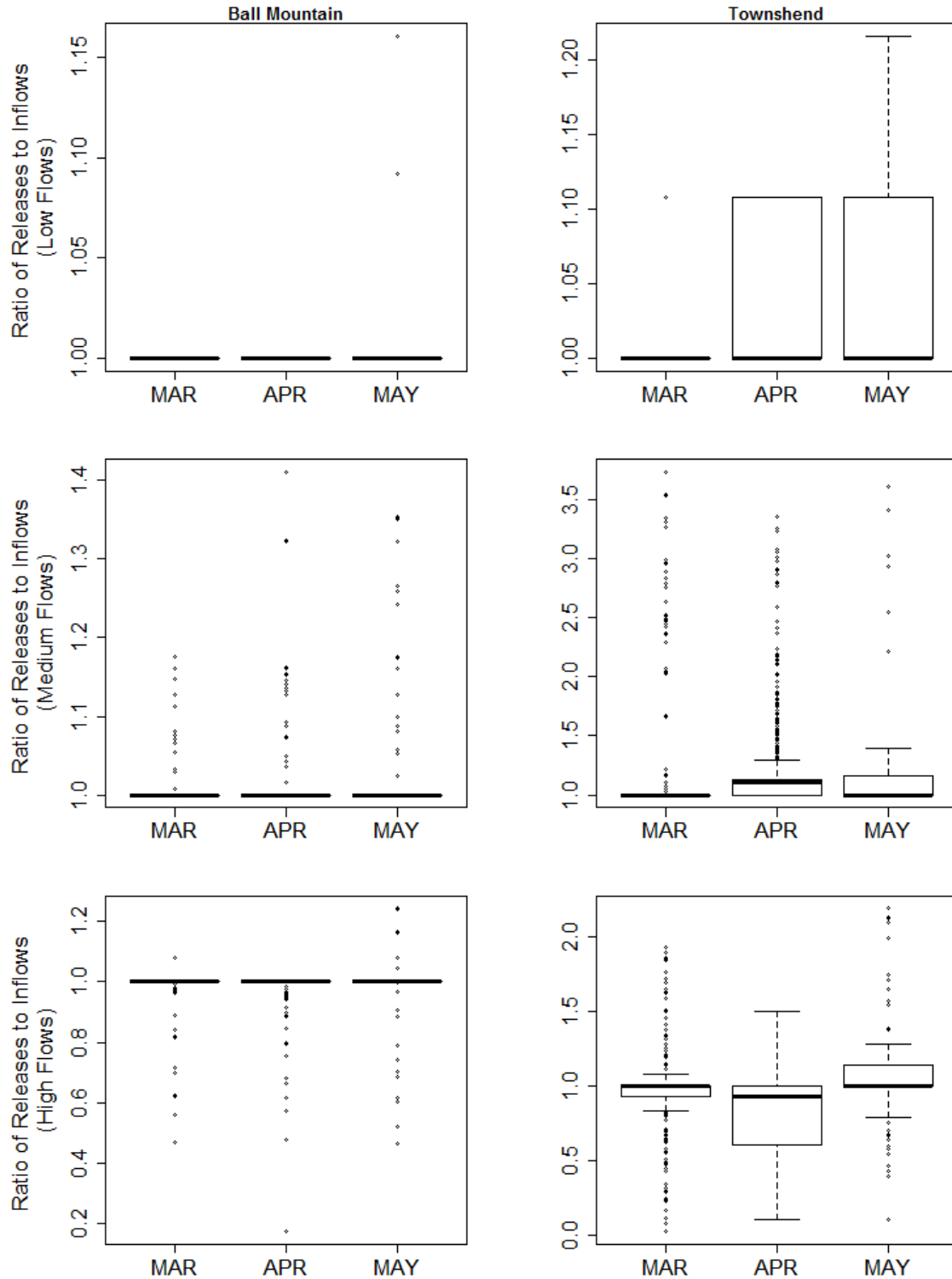


Figure A 7: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.30” run, for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

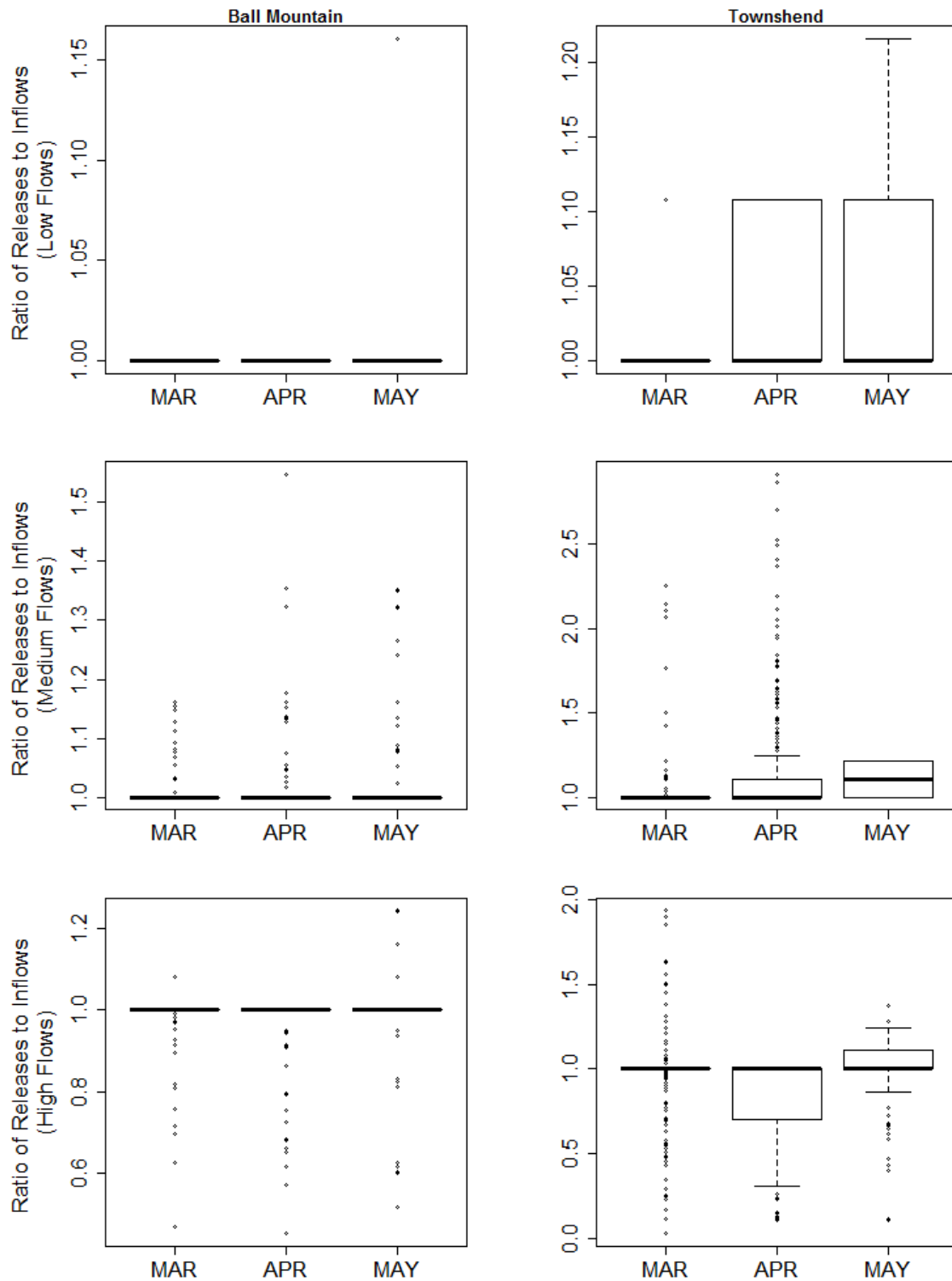


Figure A 8: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.20” run, for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

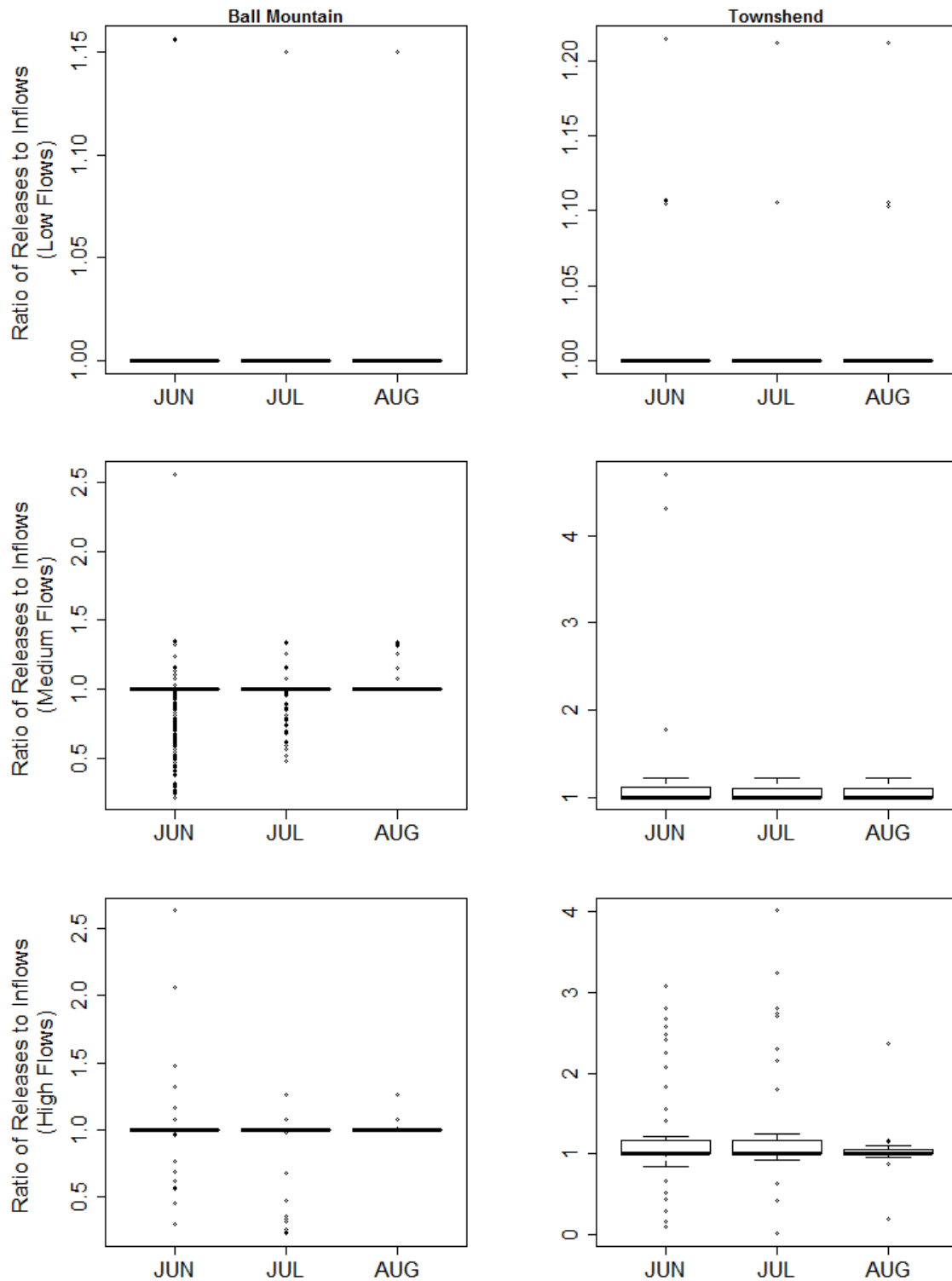


Figure A 9: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.30” run, for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

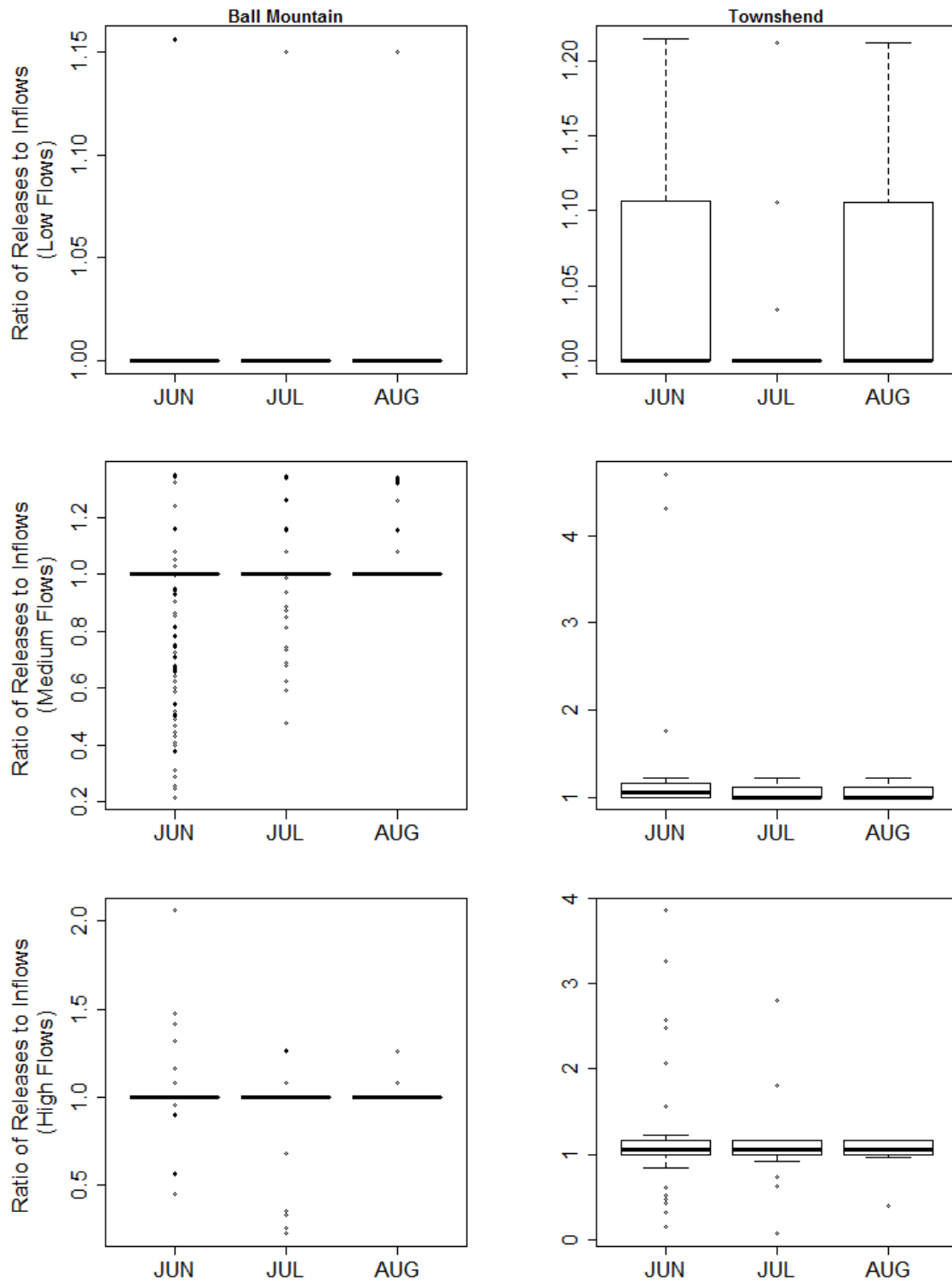


Figure A 10: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.20” run, for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

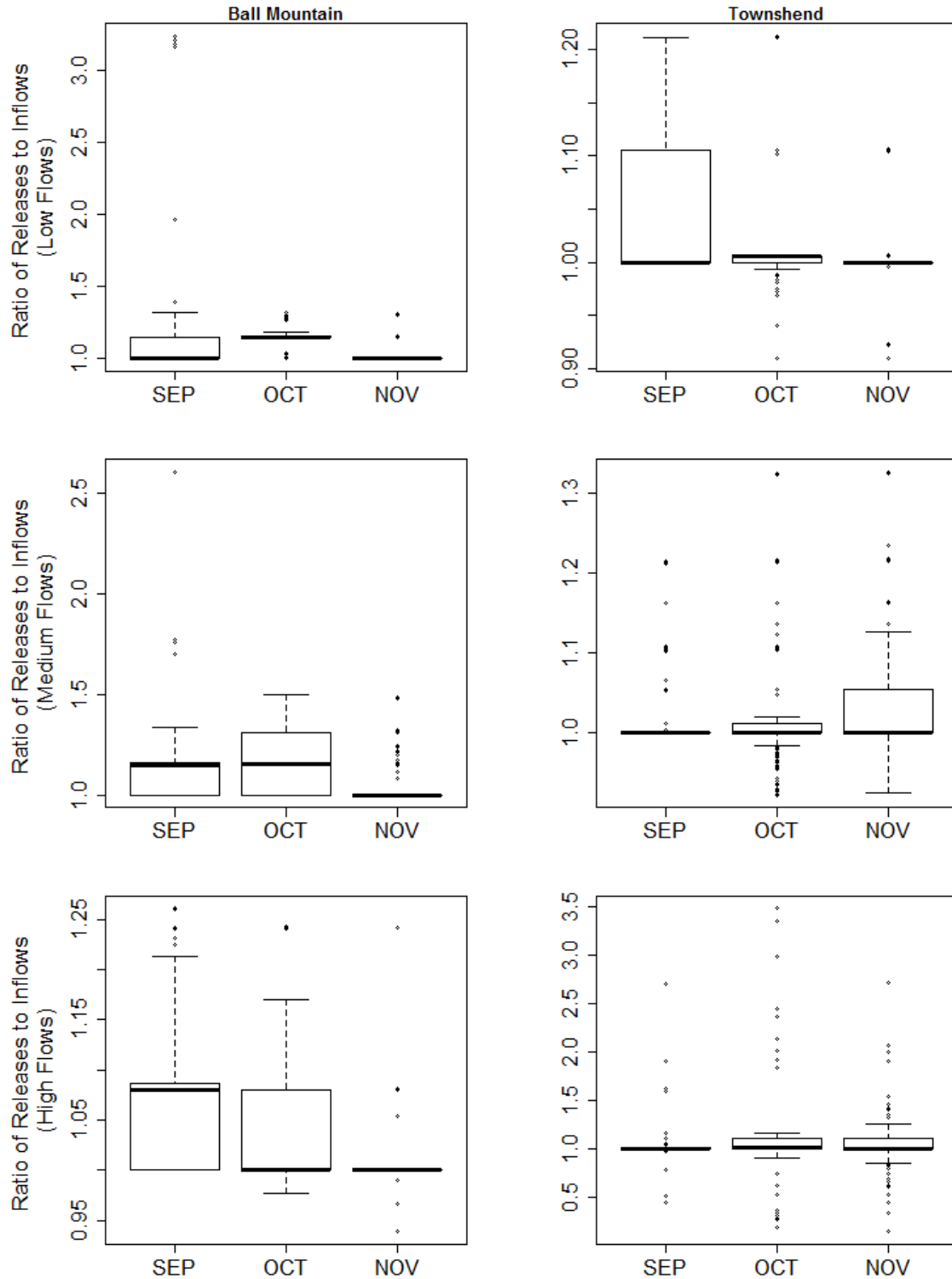


Figure A 11: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.30” run, for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

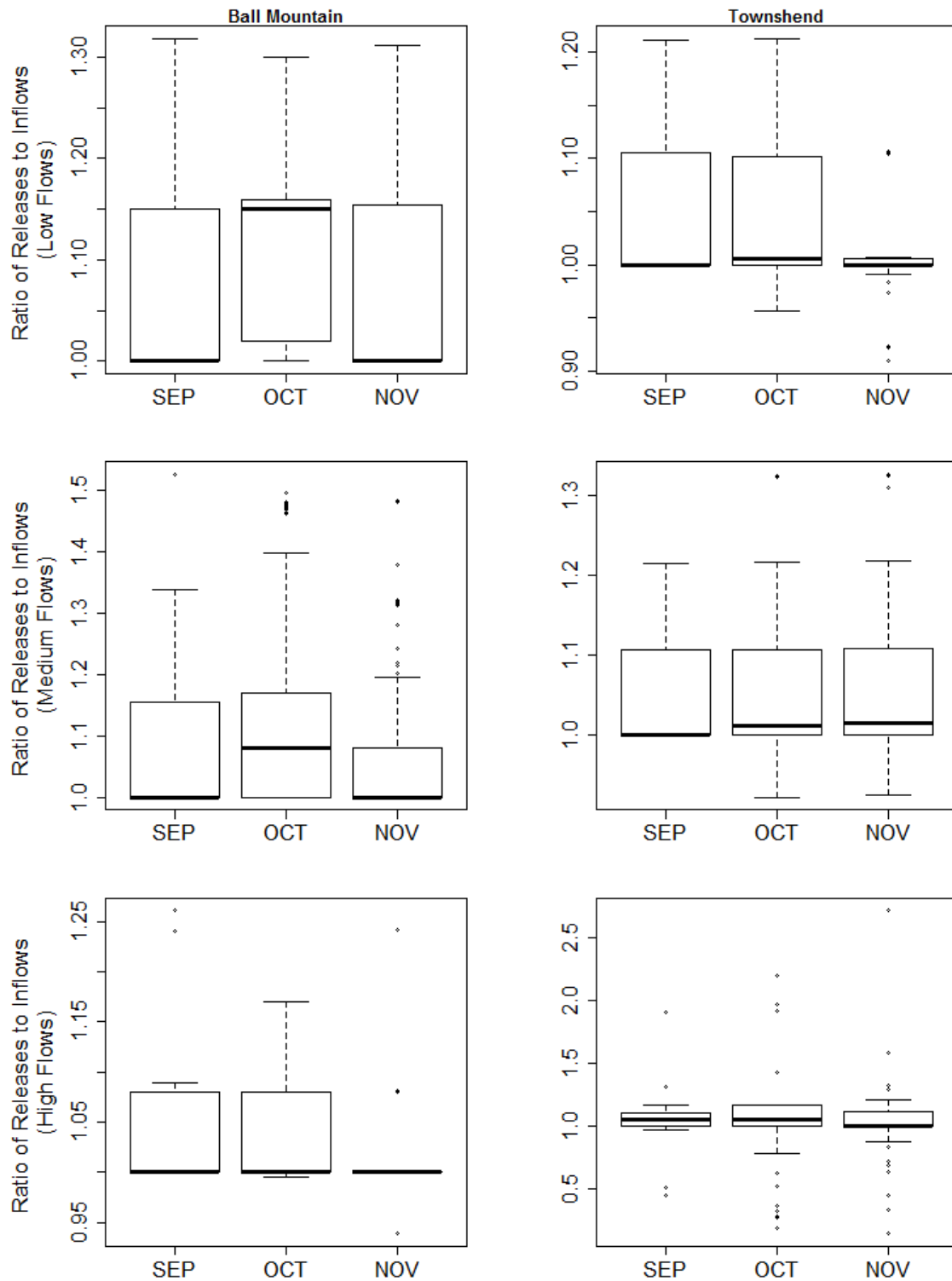


Figure A 12: Ratio of releases to inflows in West Sub-Basin reservoirs under the “ECO_RUN_0.20” run, for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

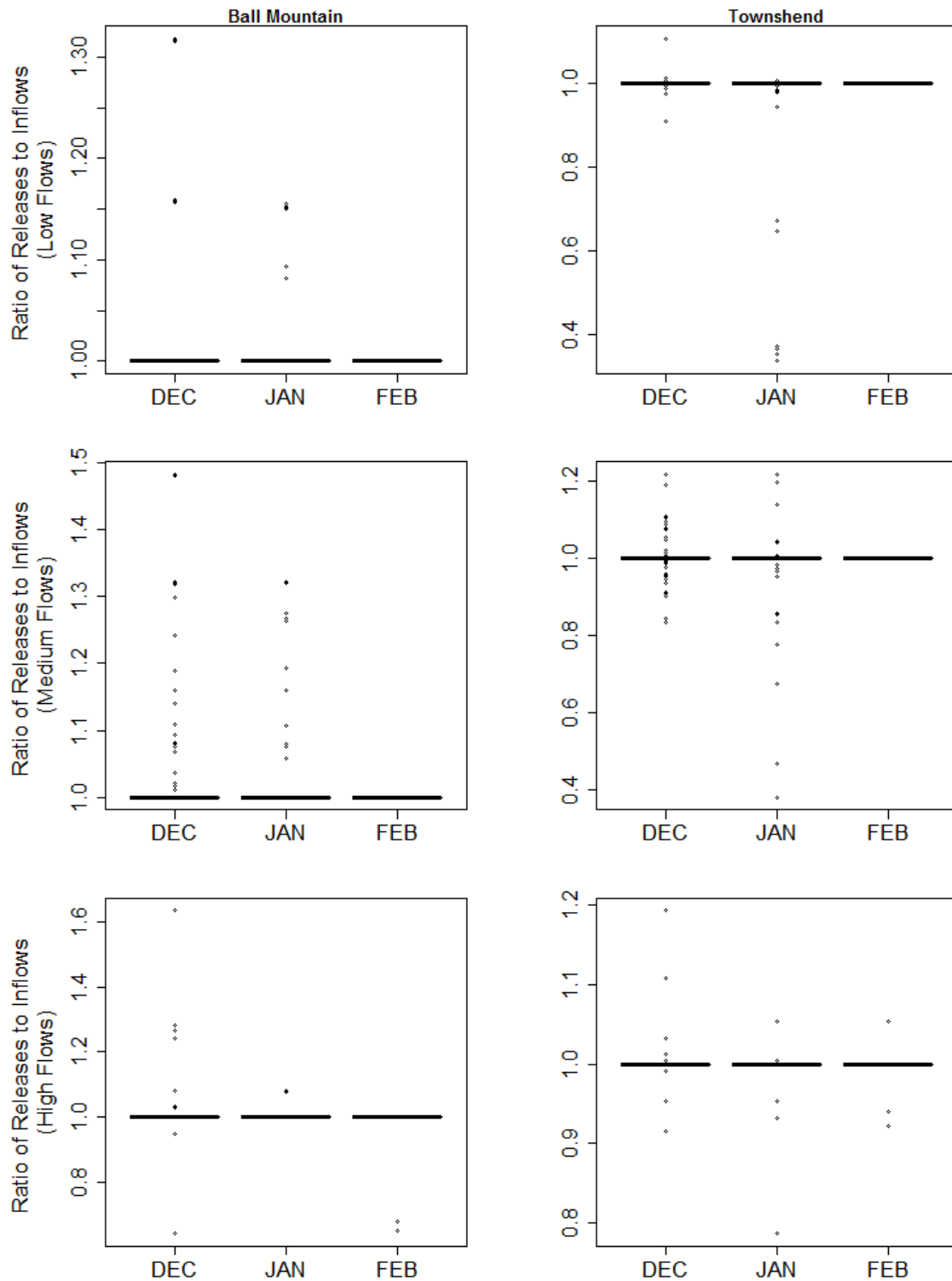


Figure A 13: Ratio of releases to inflows in West Sub-Basin reservoirs under the e-flow target run, for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

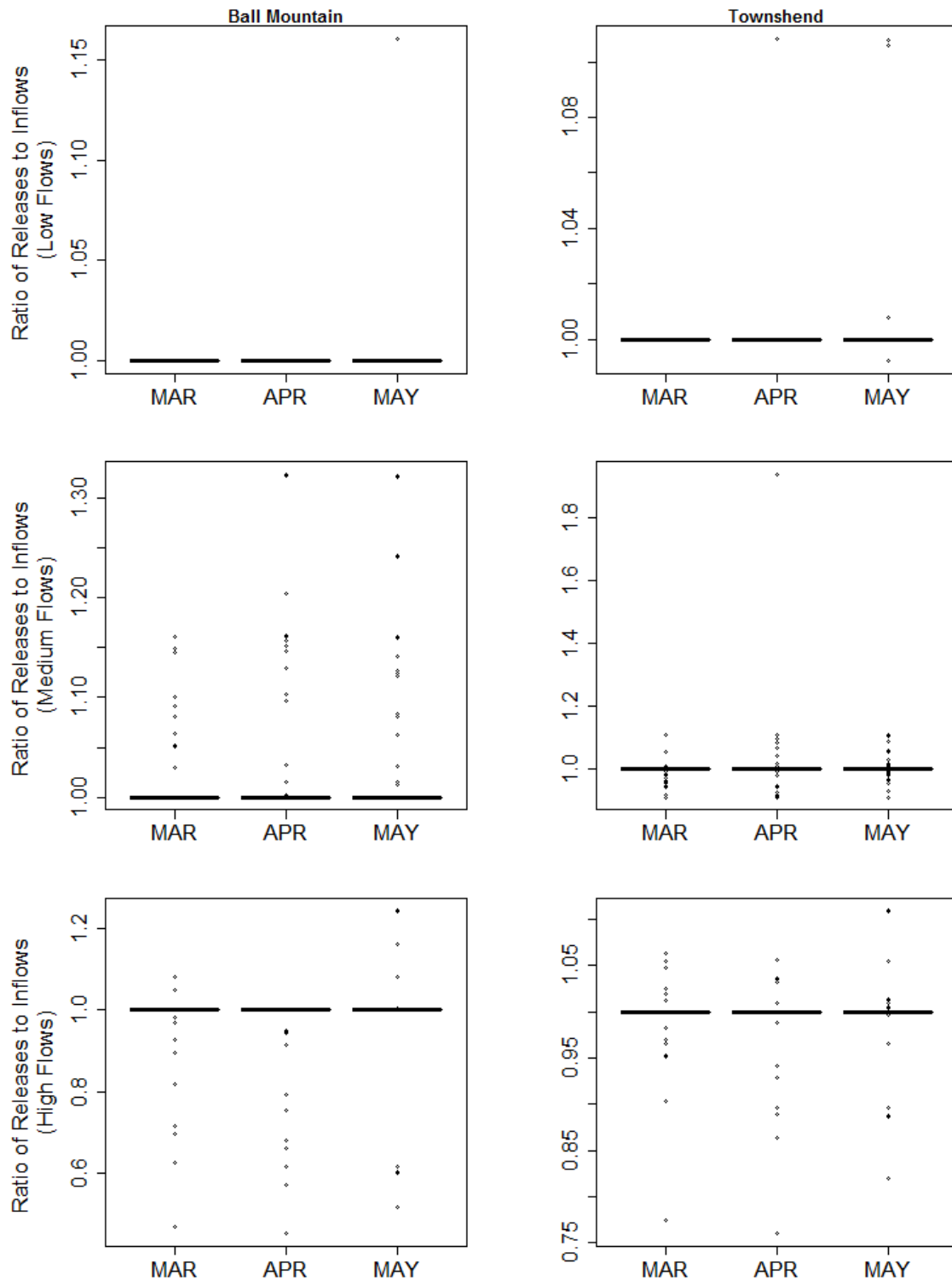


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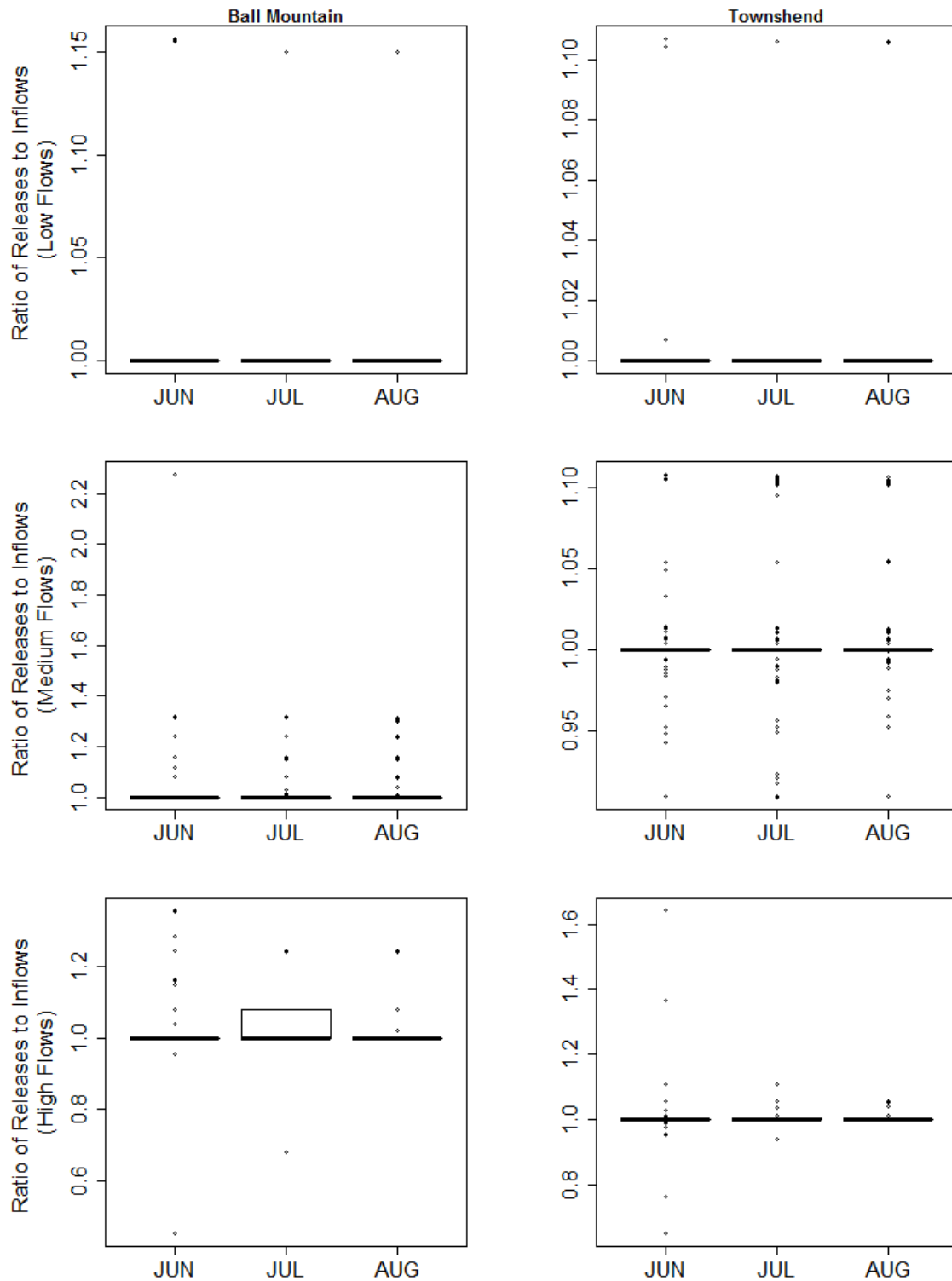


Figure A 15: Ratio of releases to inflows in West Sub-Basin reservoirs under the e-flow target run, for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

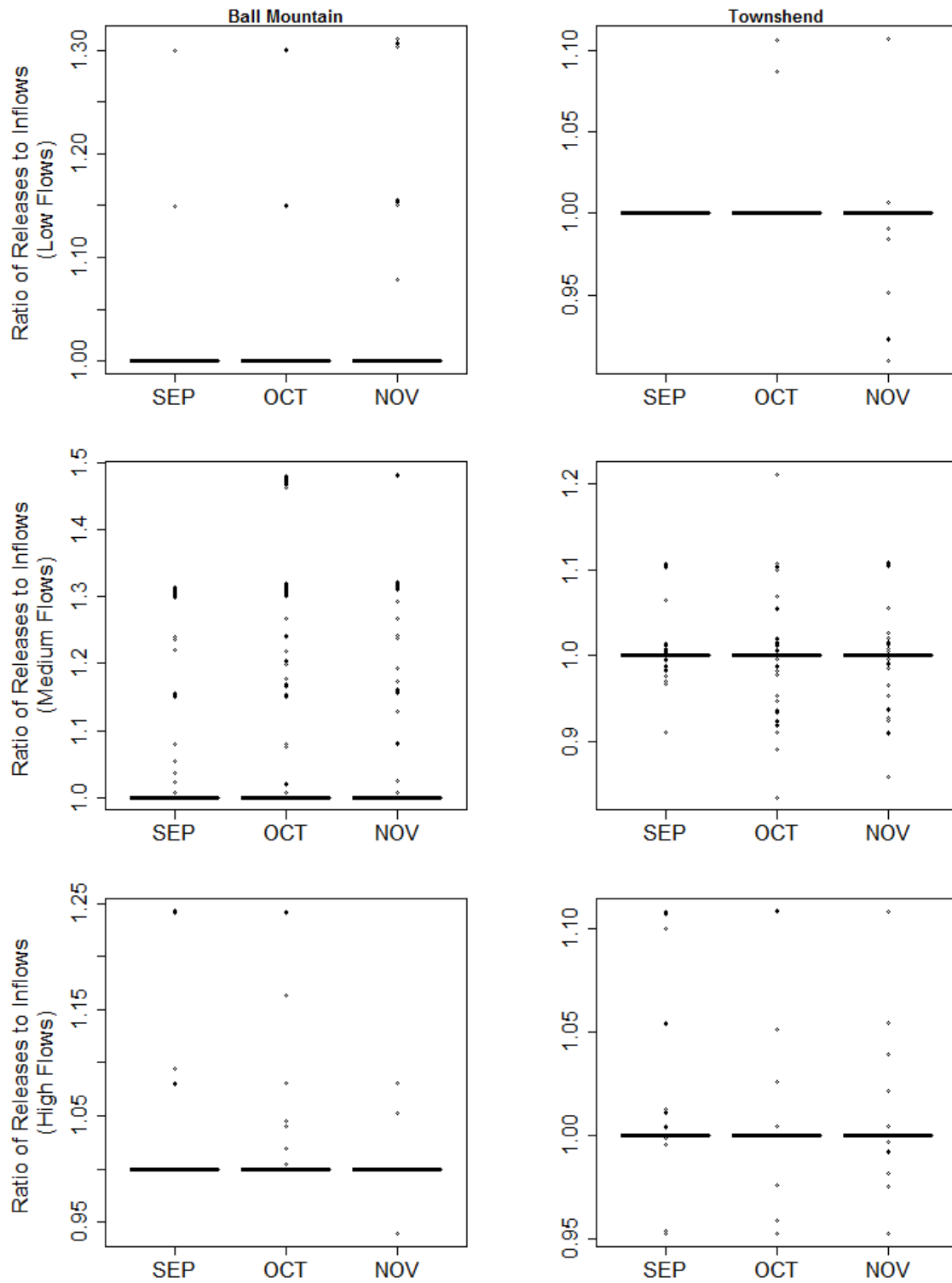


Figure A 16: Ratio of releases to inflows in West Sub-Basin reservoirs under the e-flow target run for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

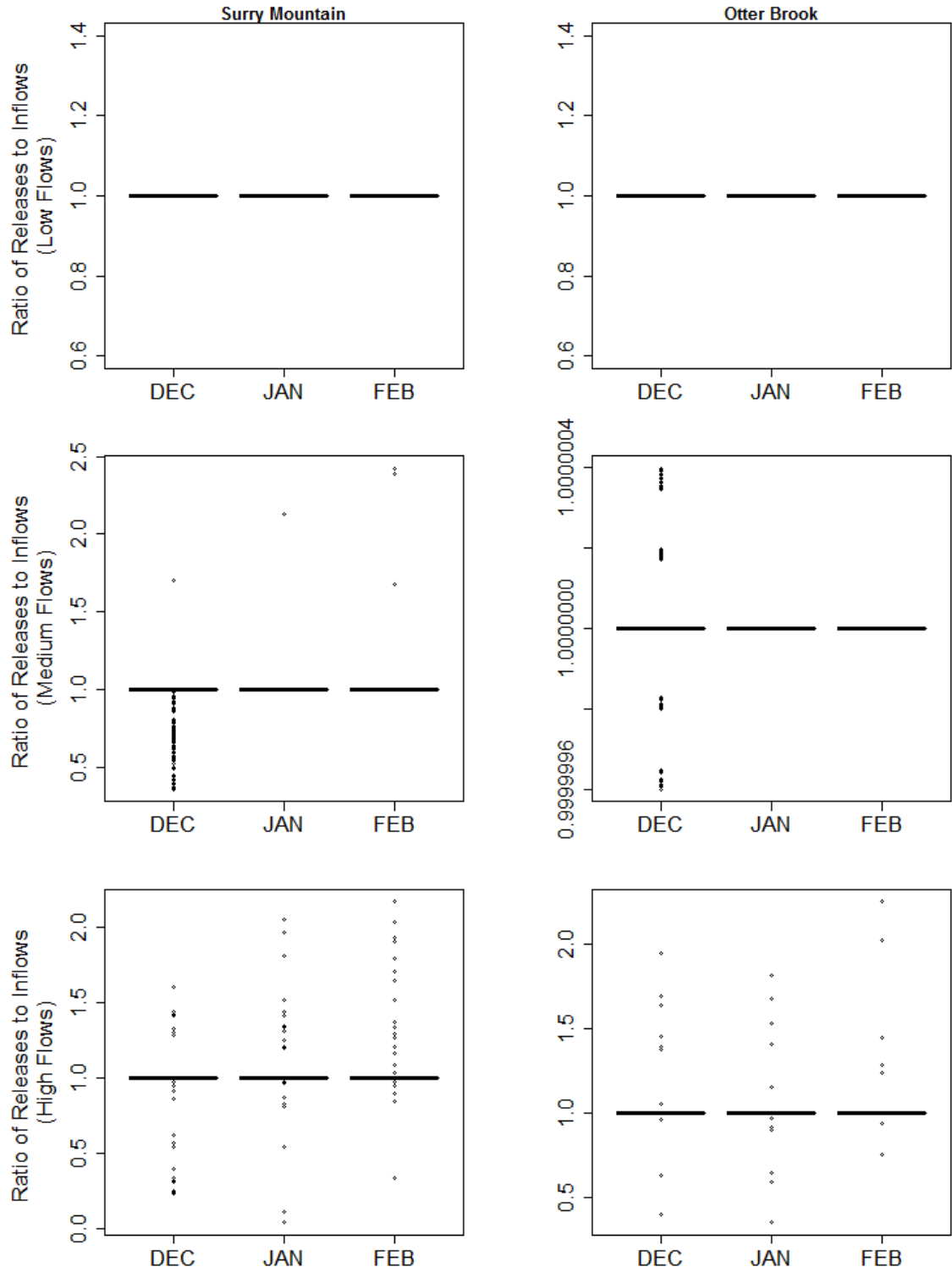


Figure A 17: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the status-quo run, for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

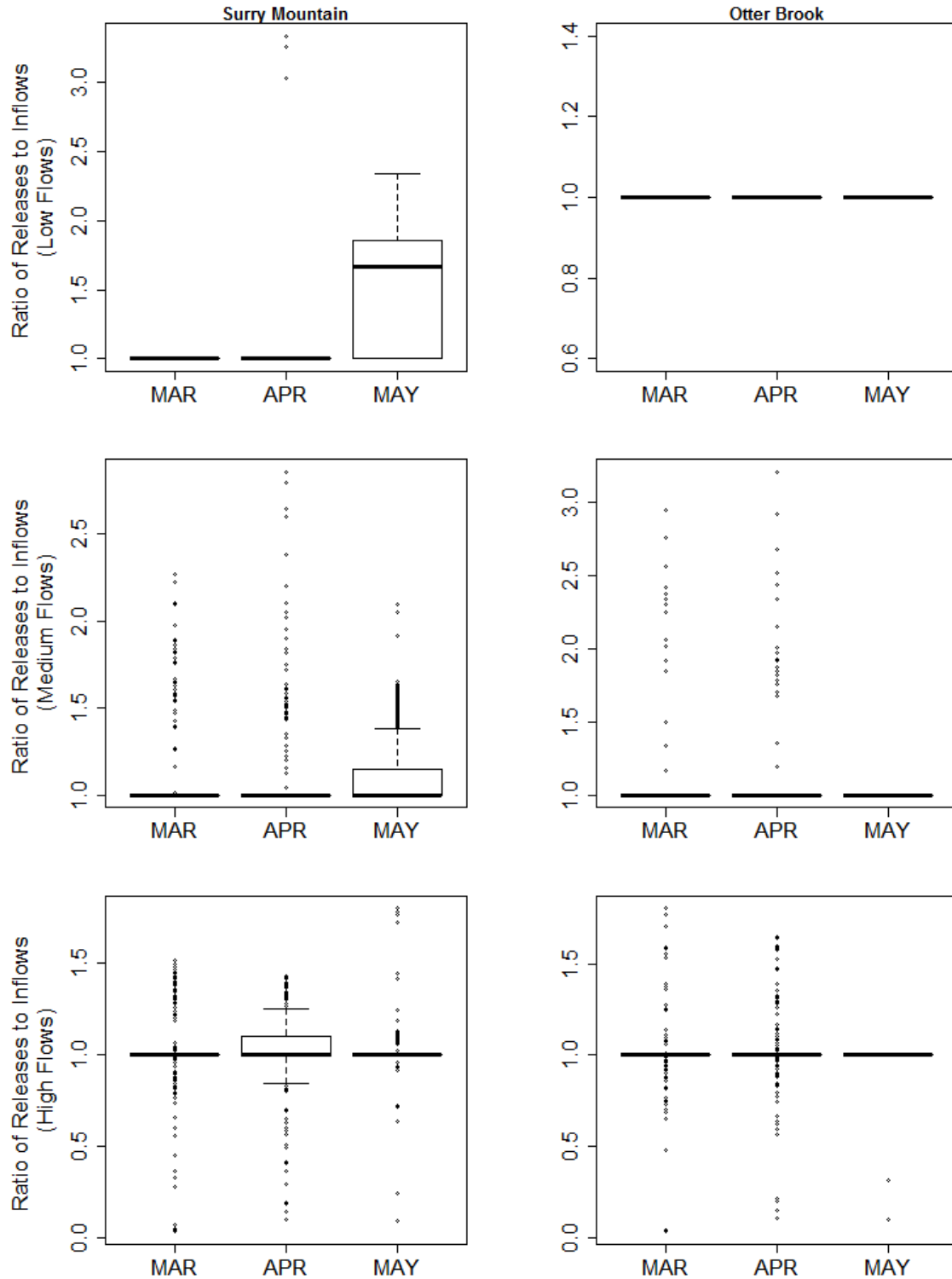


Figure A 18: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the status-quo run for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

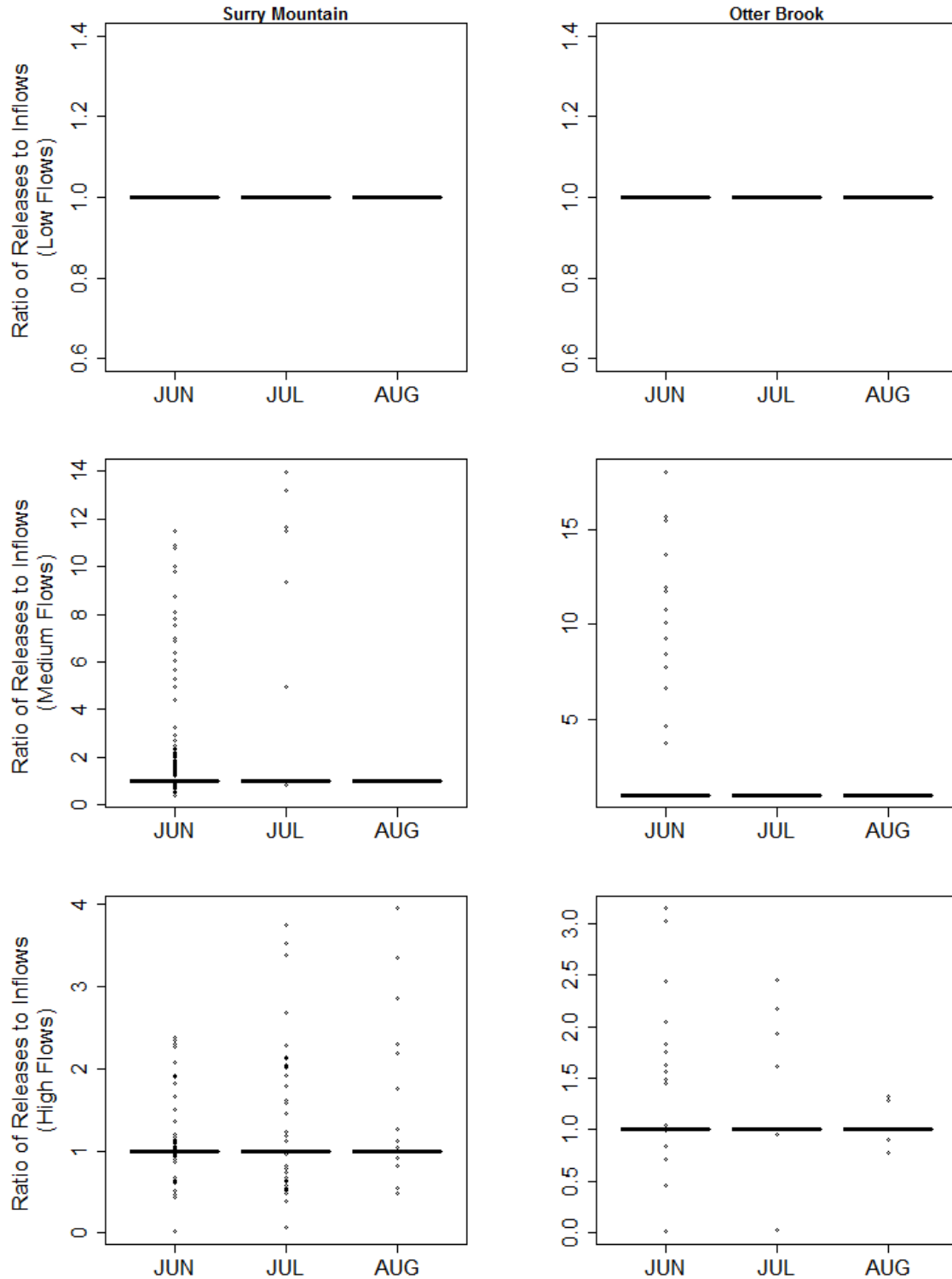


Figure A 19: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the status-quo run for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

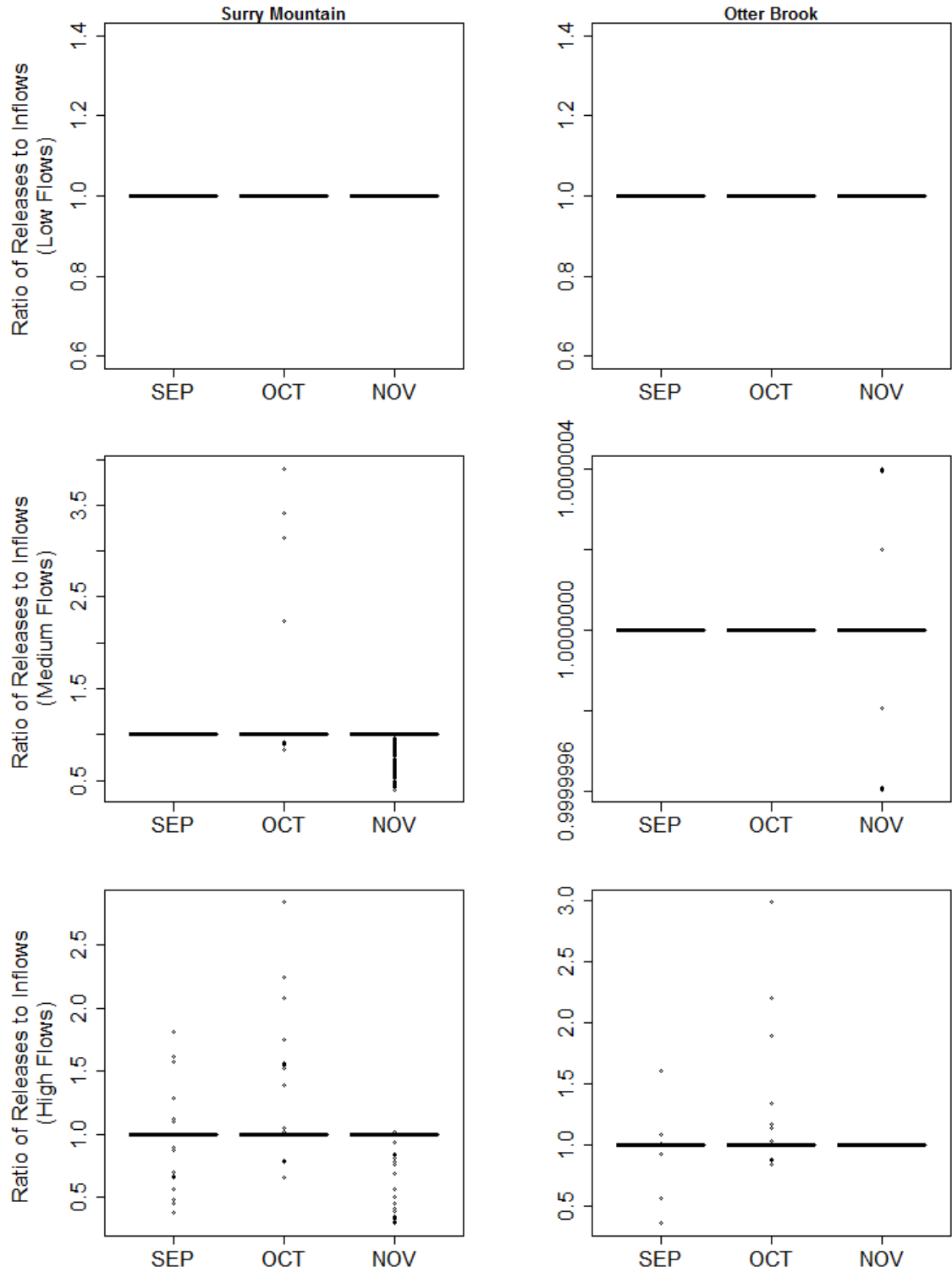


Figure A 20: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the status-quo run for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

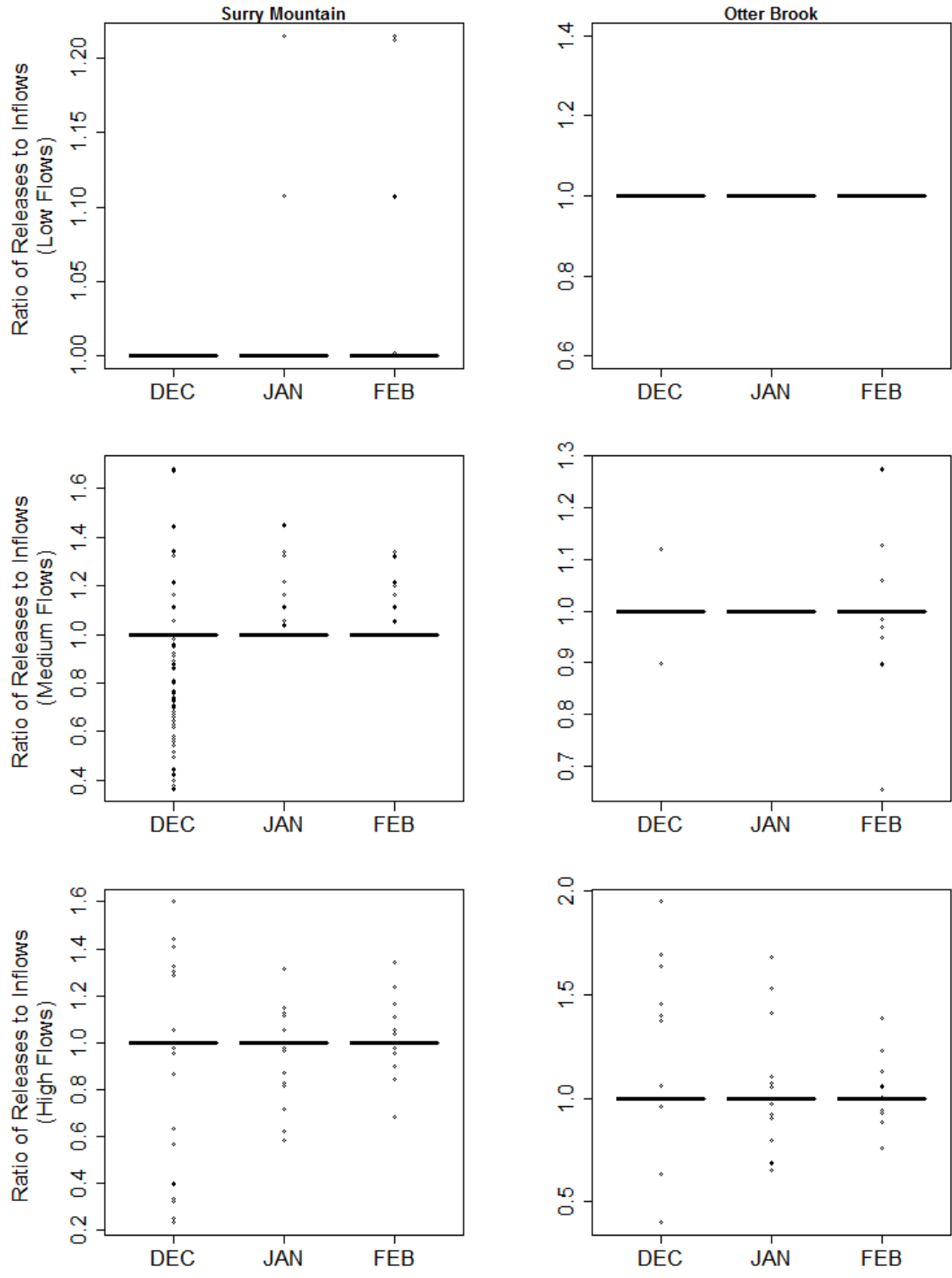


Figure A 21: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.30” run for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

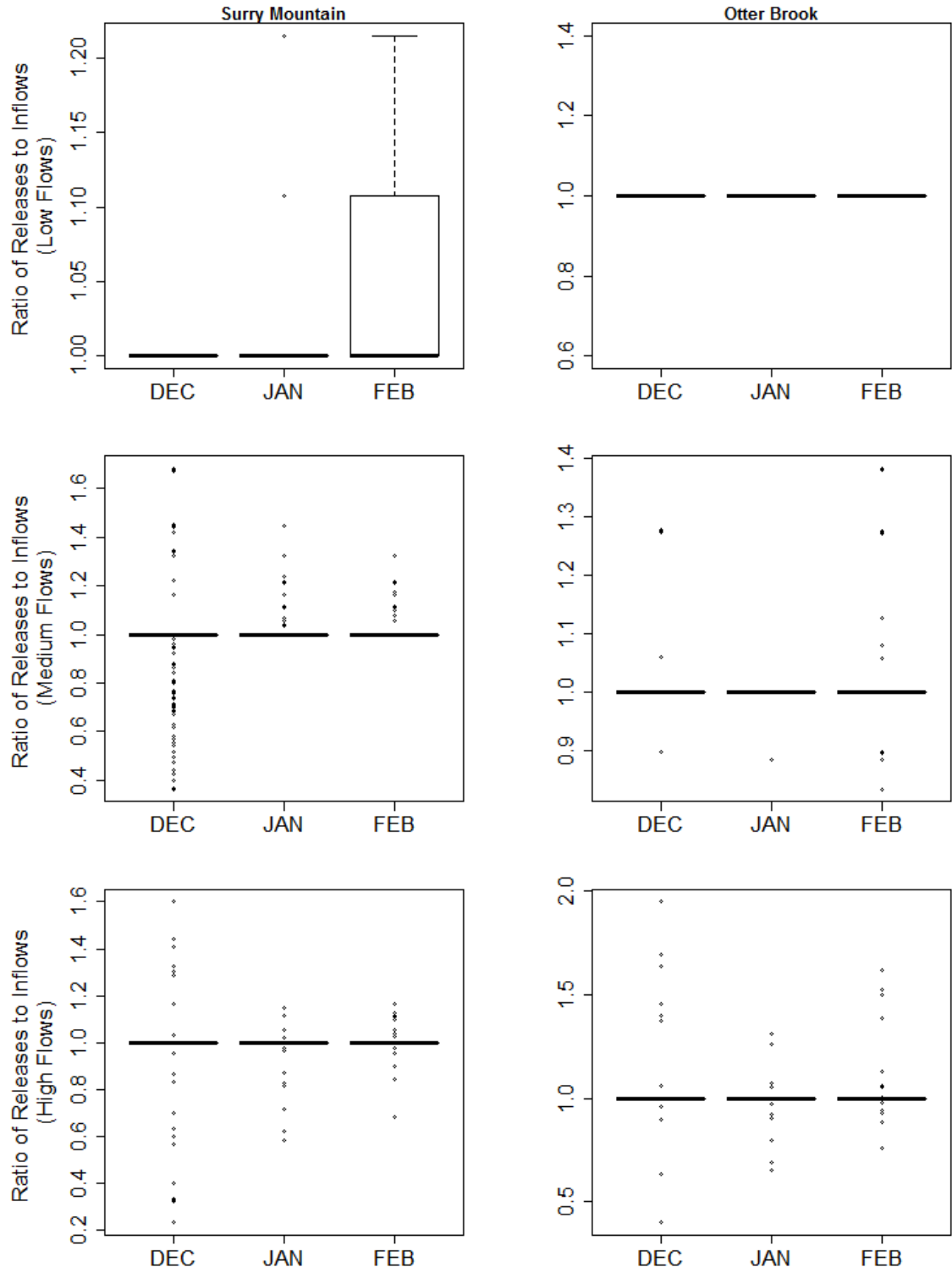


Figure A 22: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.20” run for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

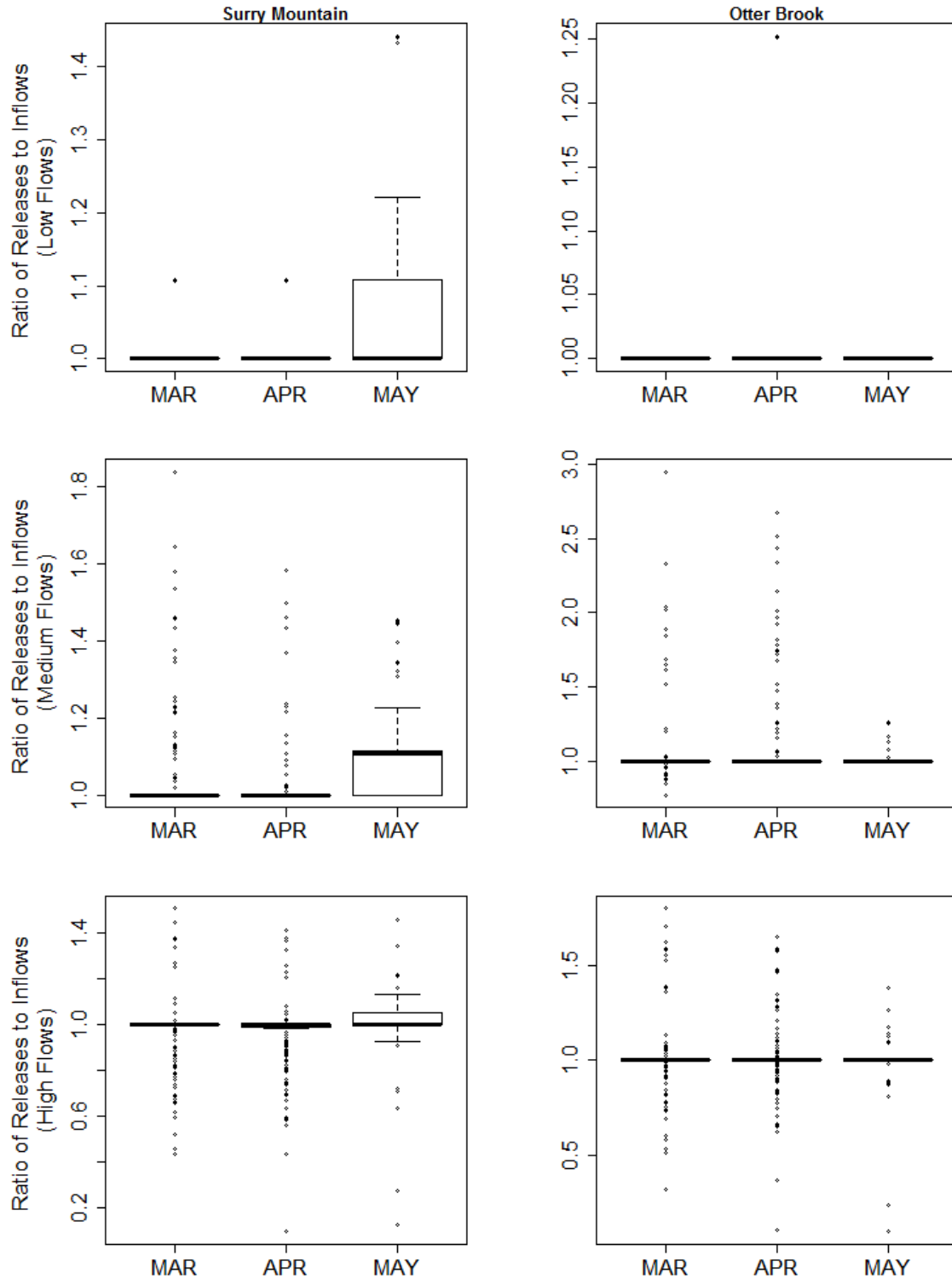


Figure A 23: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.30” run for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

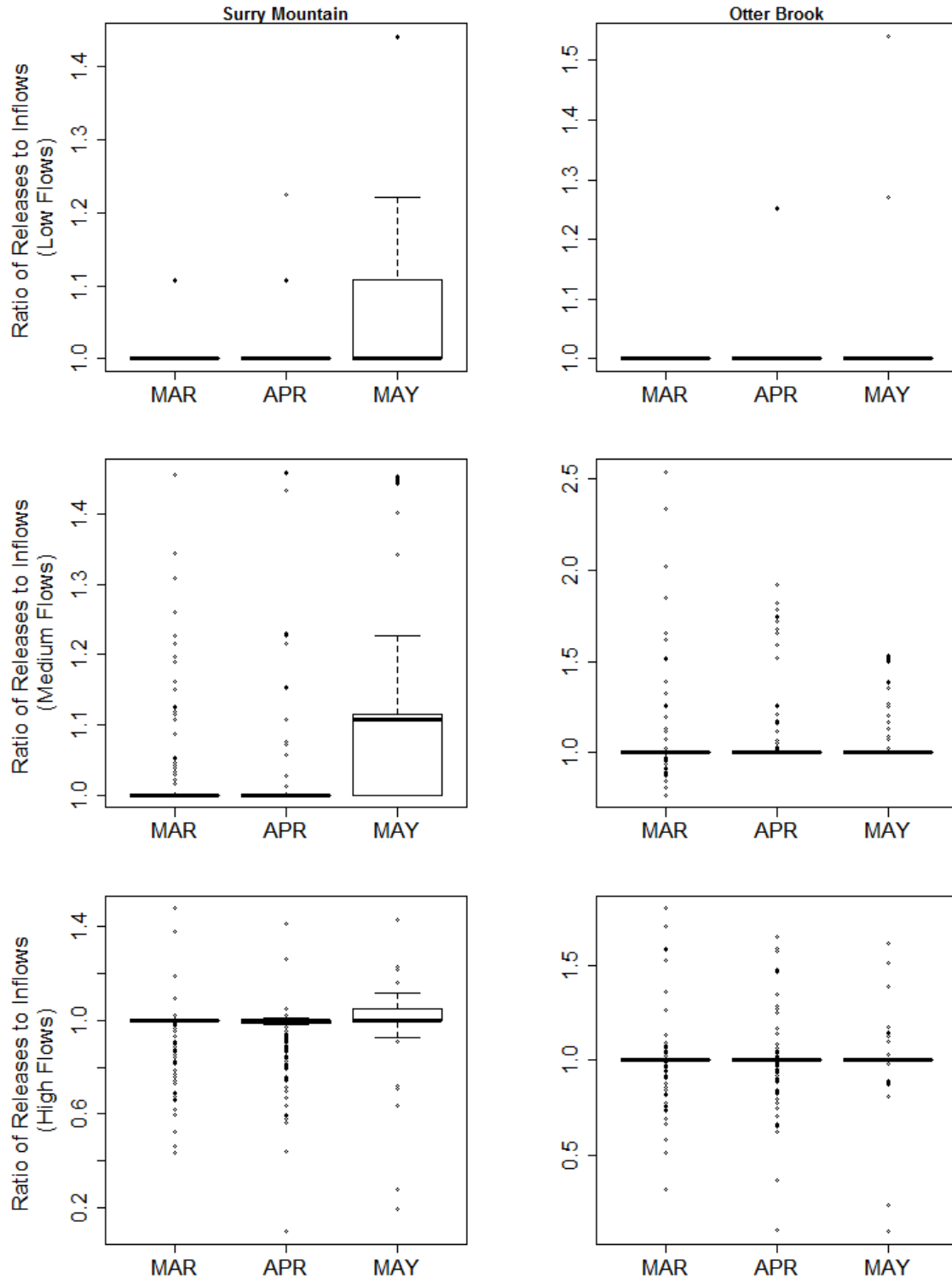


Figure A 24: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.20” run for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

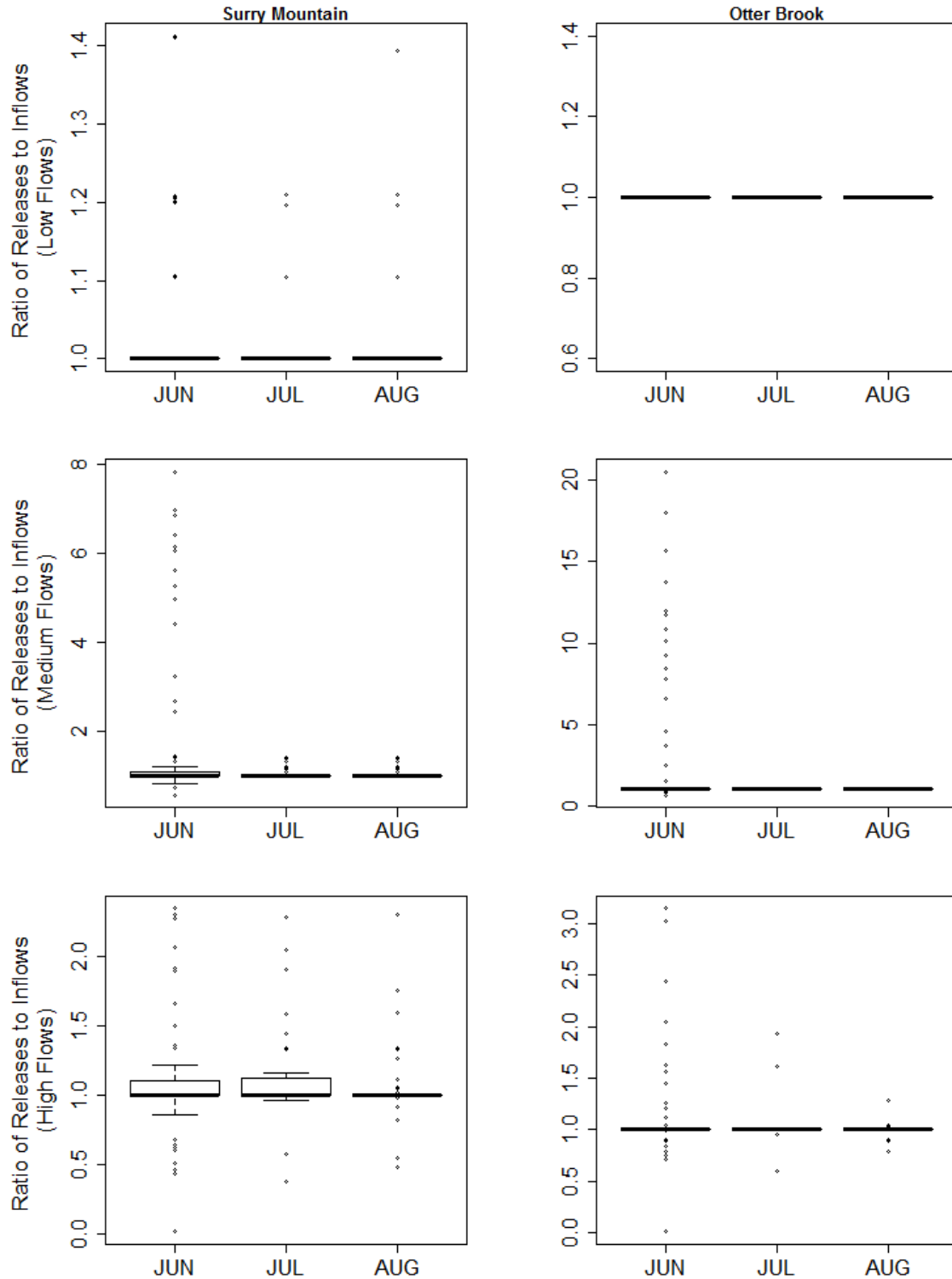


Figure A 25: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.30” run for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

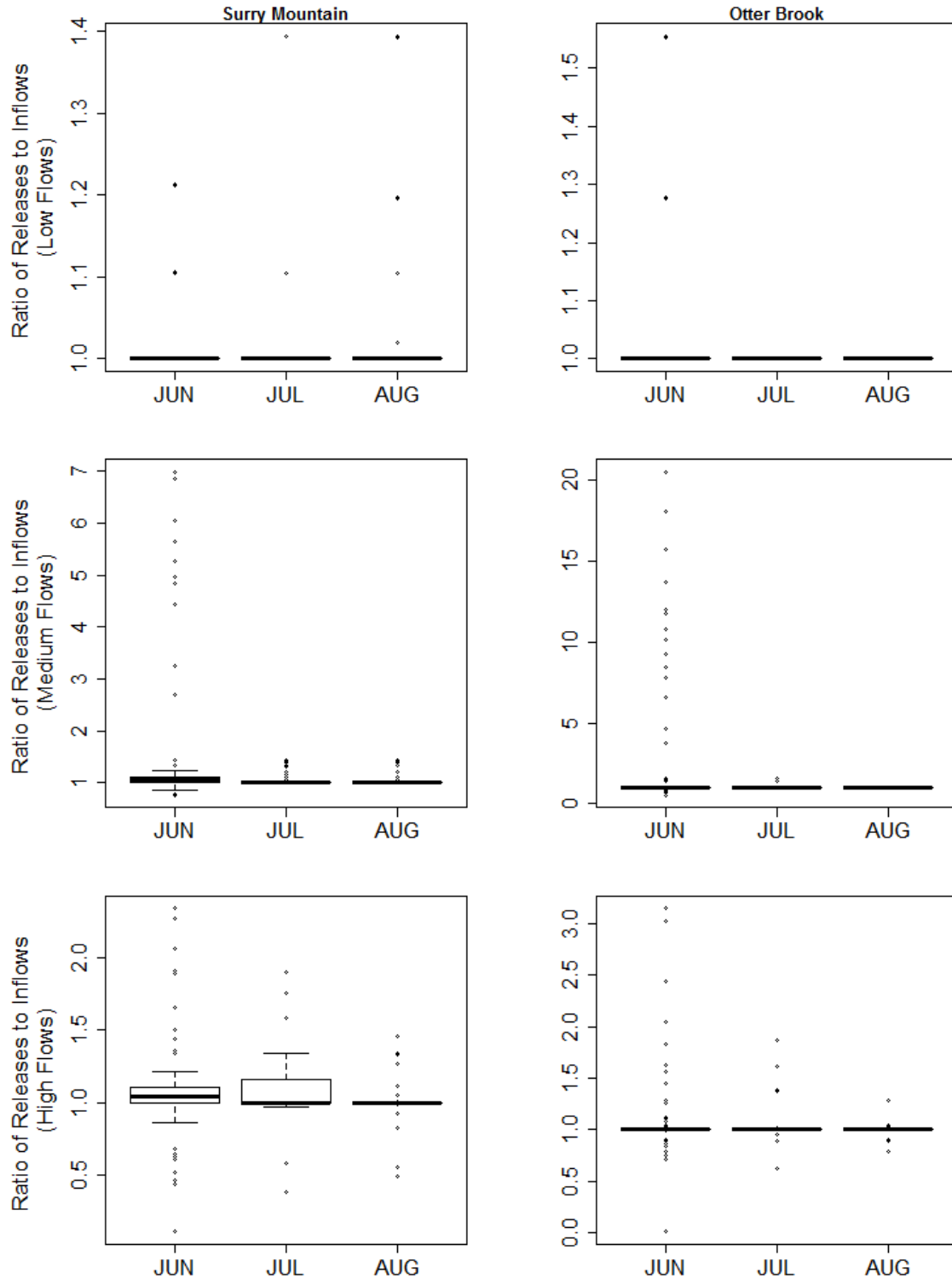


Figure A 26: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.20” run for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

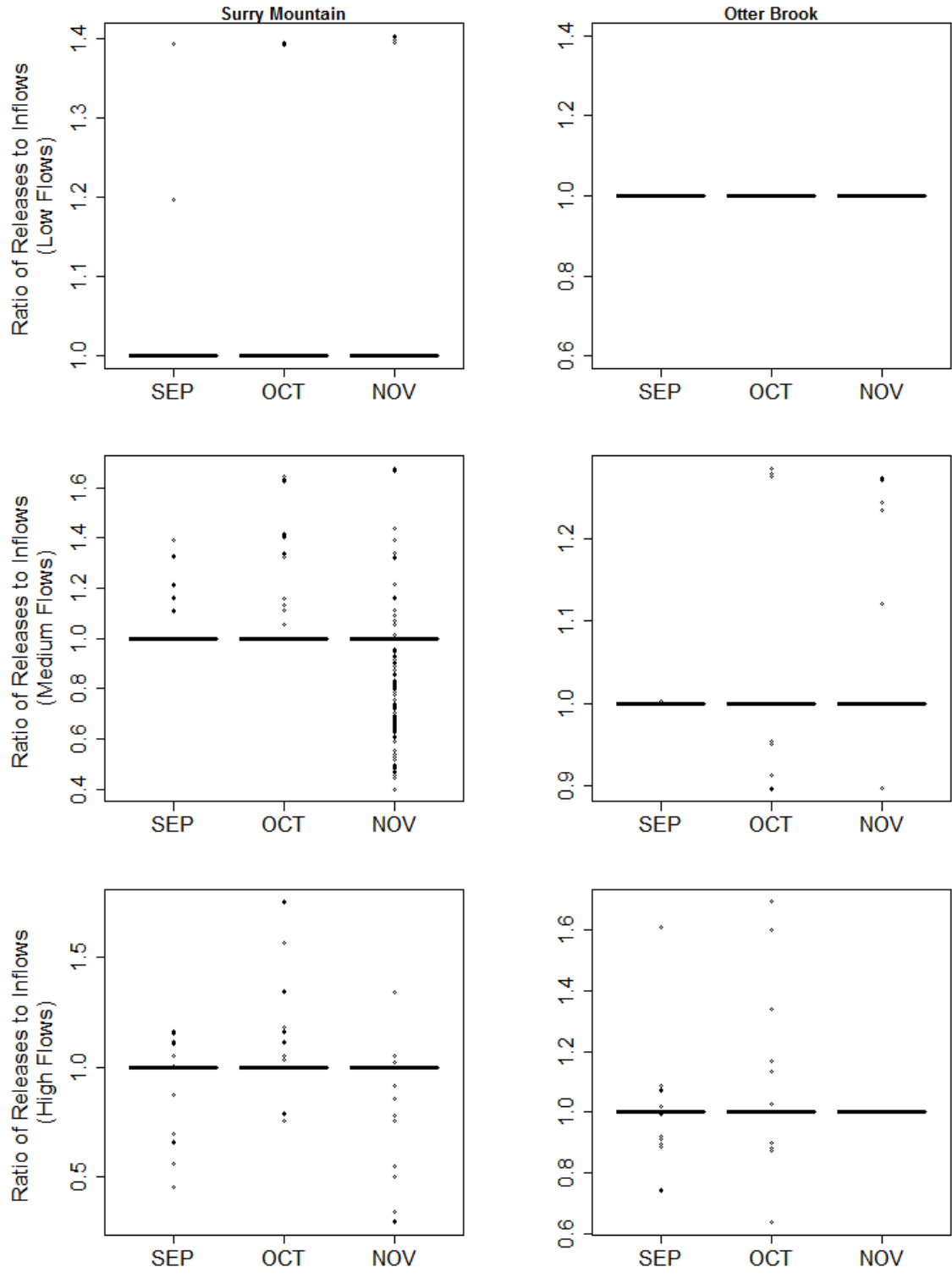


Figure A 27: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.30” run for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

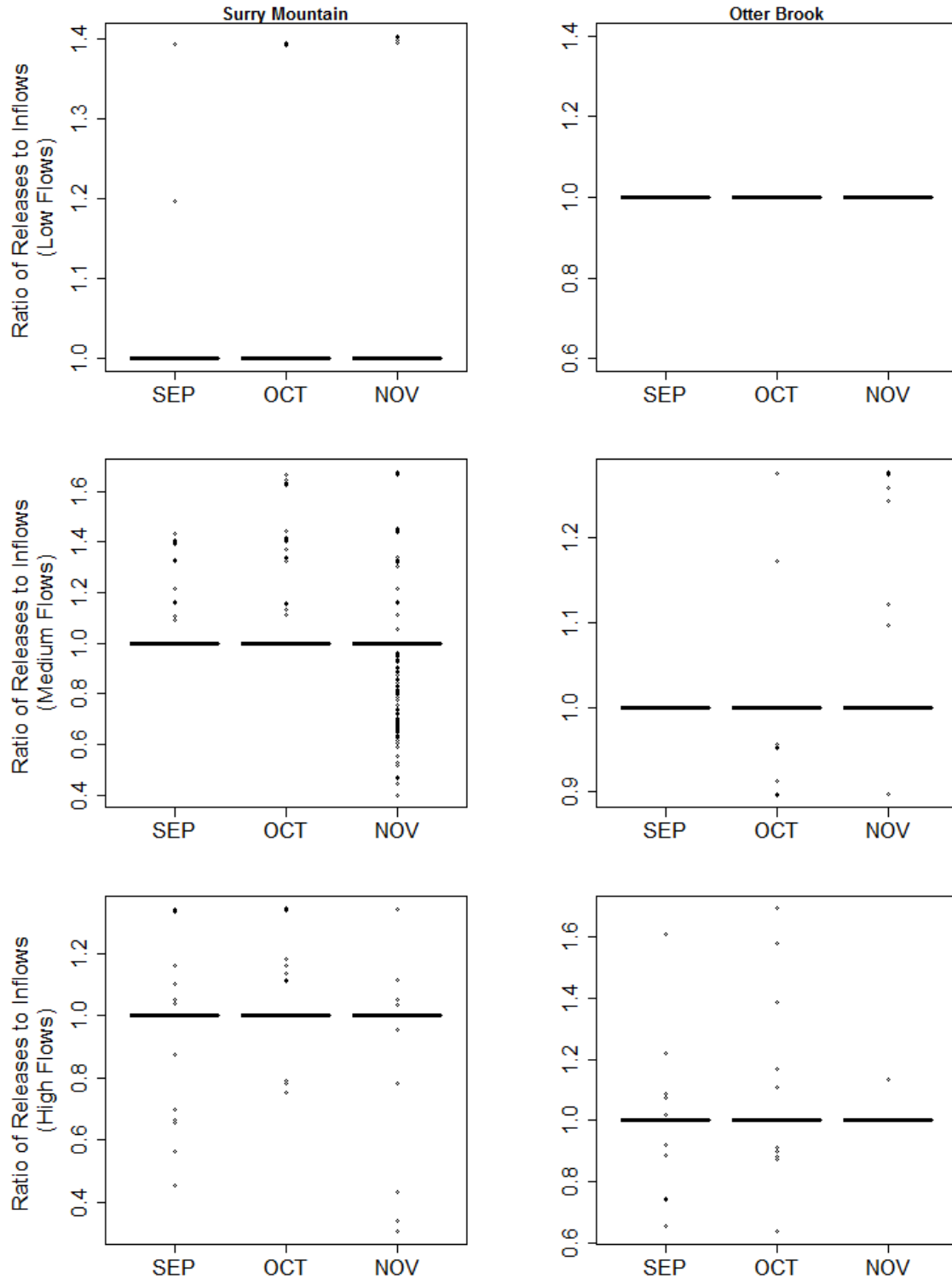


Figure A 28: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the “ECO_RUN_0.20” run for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

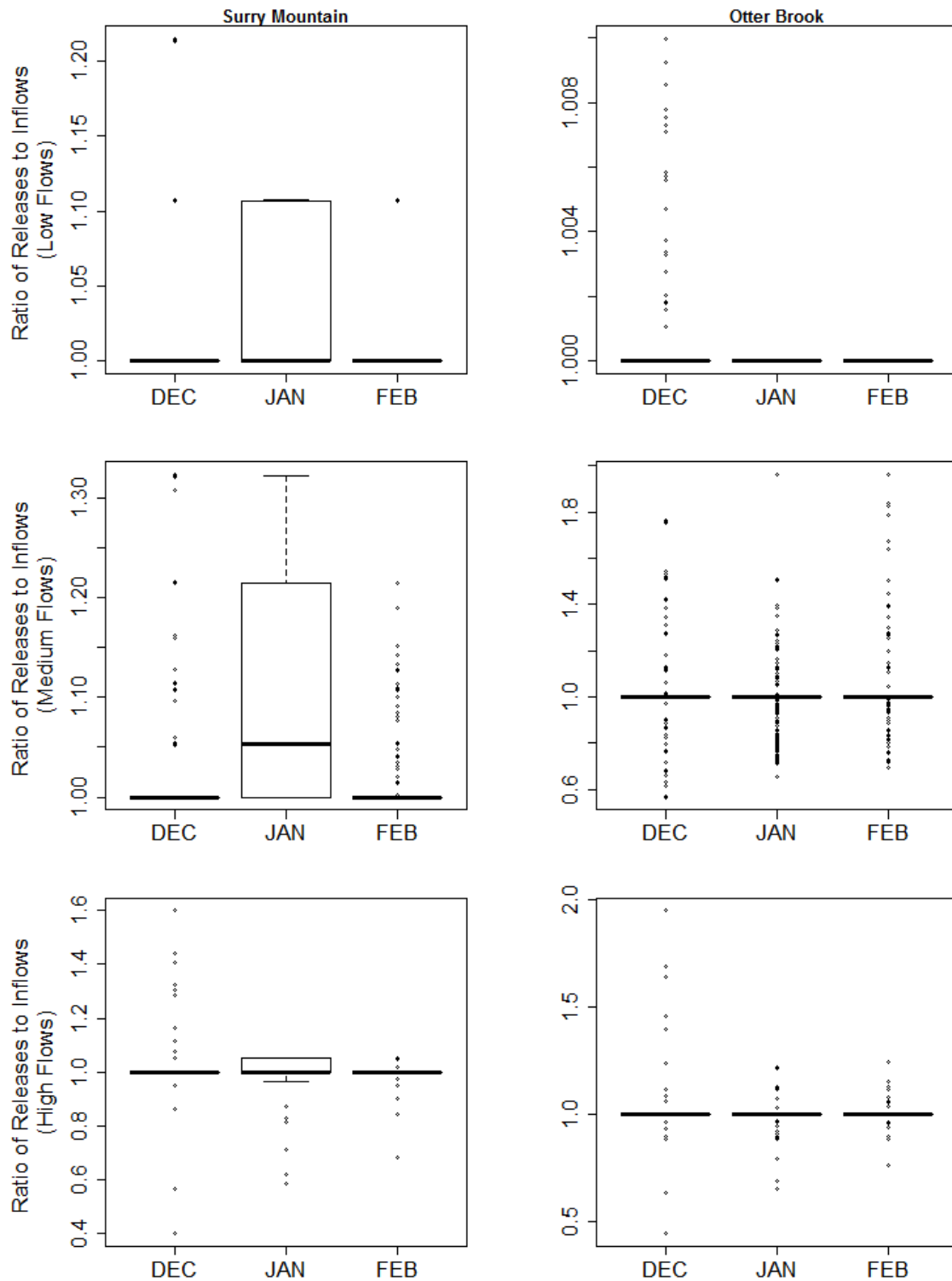


Figure A 29: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the e-flow target run for winter months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

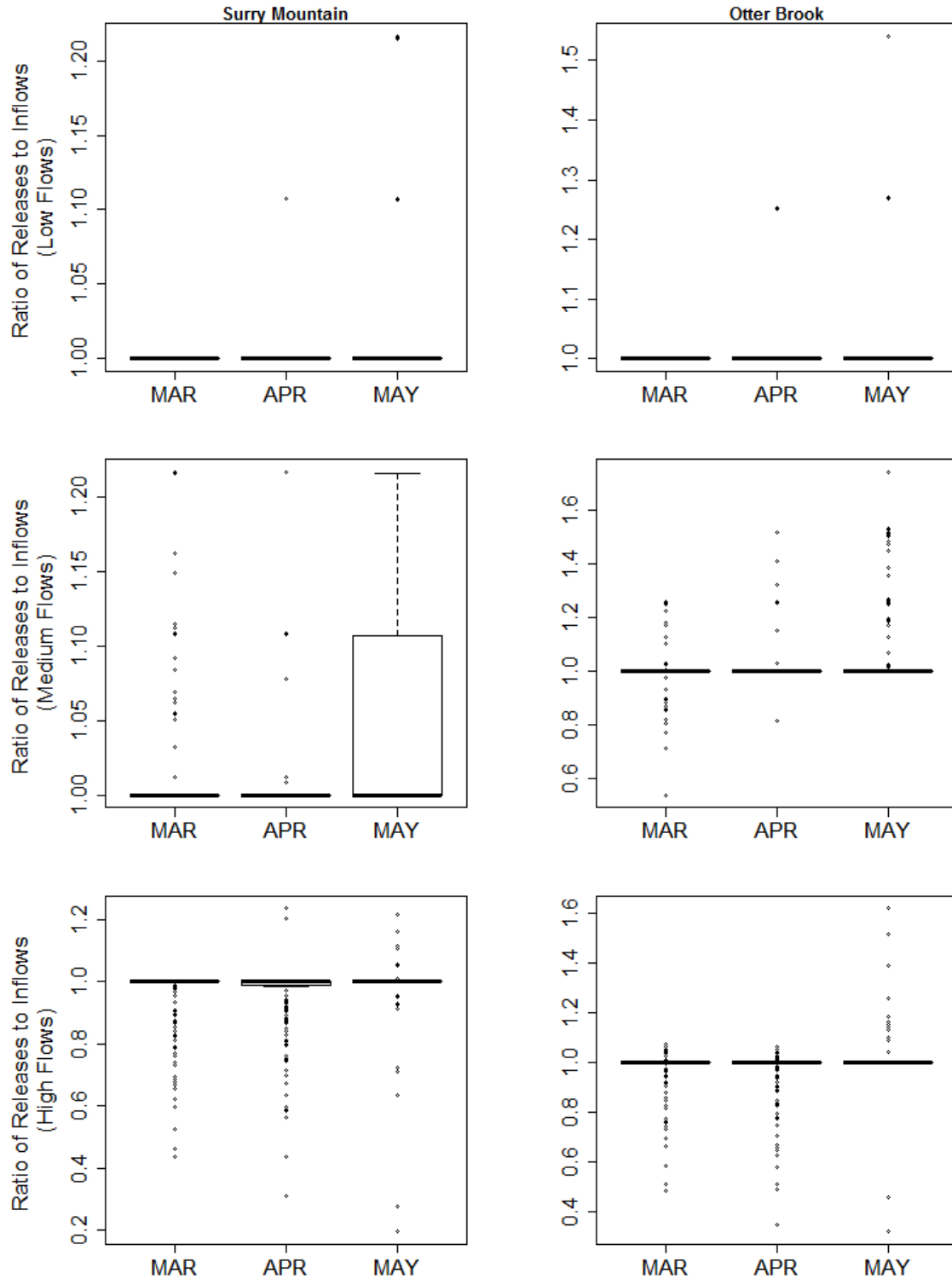


Figure A 30: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the e-flow target run for spring months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

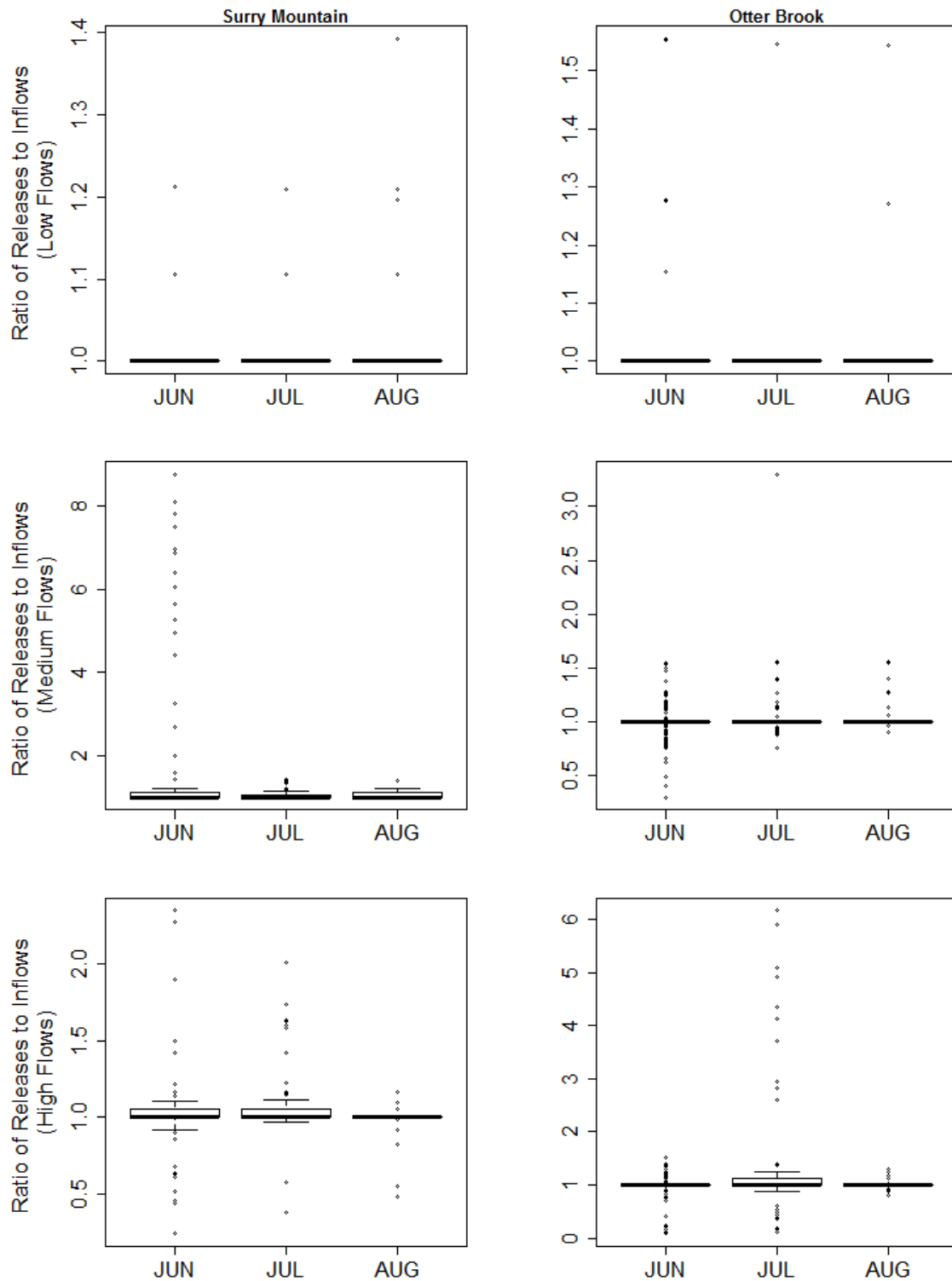


Figure A 31: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the e-flow target run for summer months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

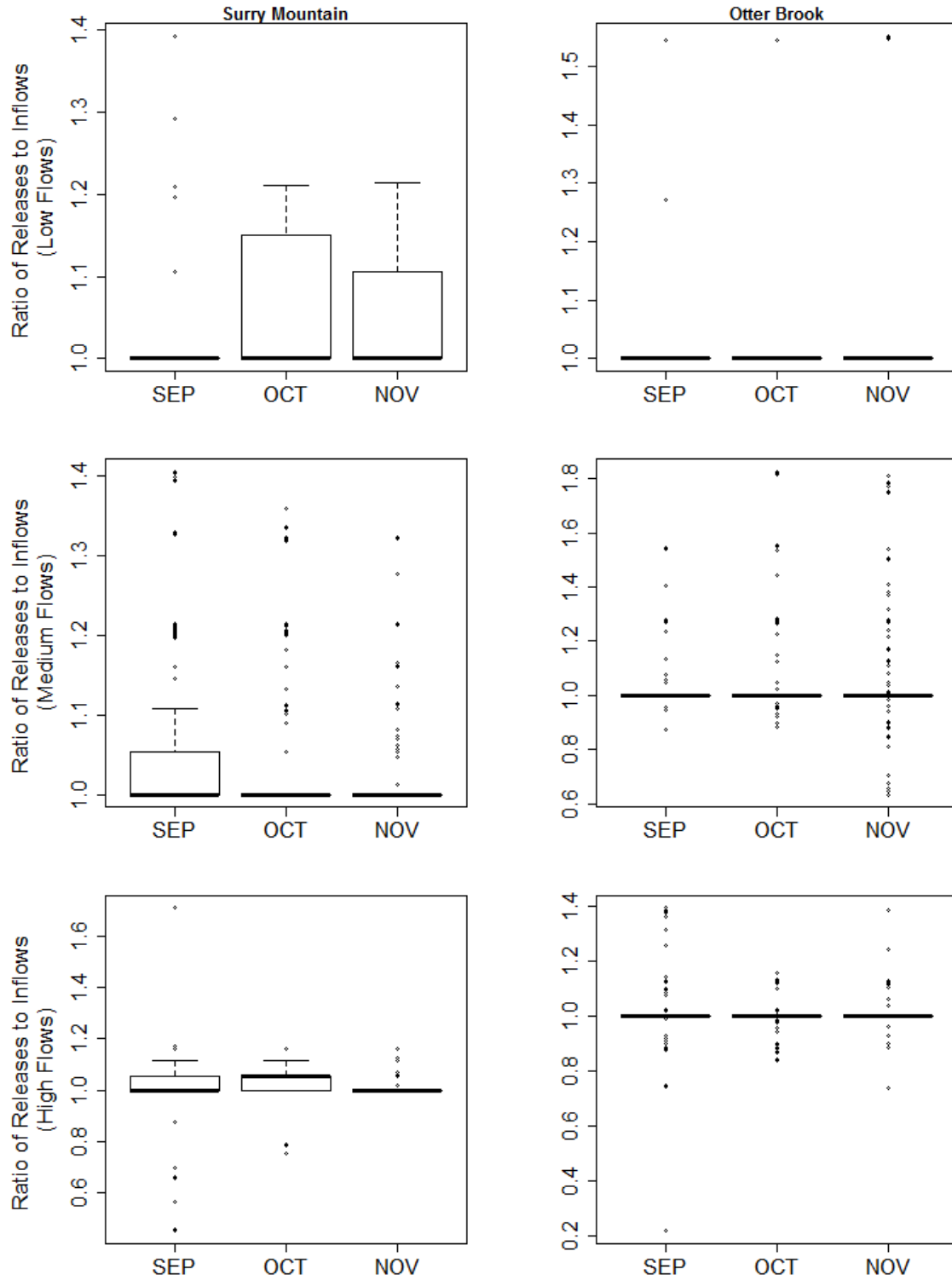
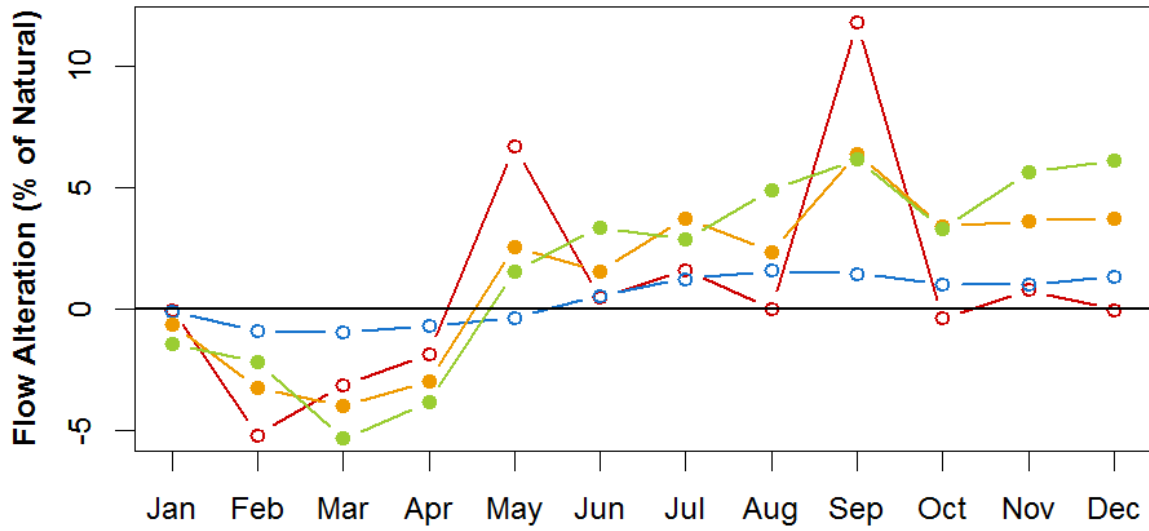


Figure A 32: Ratio of releases to inflows in Ashuelot Sub-Basin reservoirs under the e-flow target run for fall months, sorted by inflow volume: (a) lowest 15%, (b) middle 70%, and (c) highest 15%

Eco-Node 33



Eco-Node 95

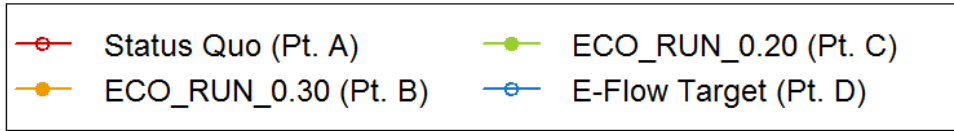
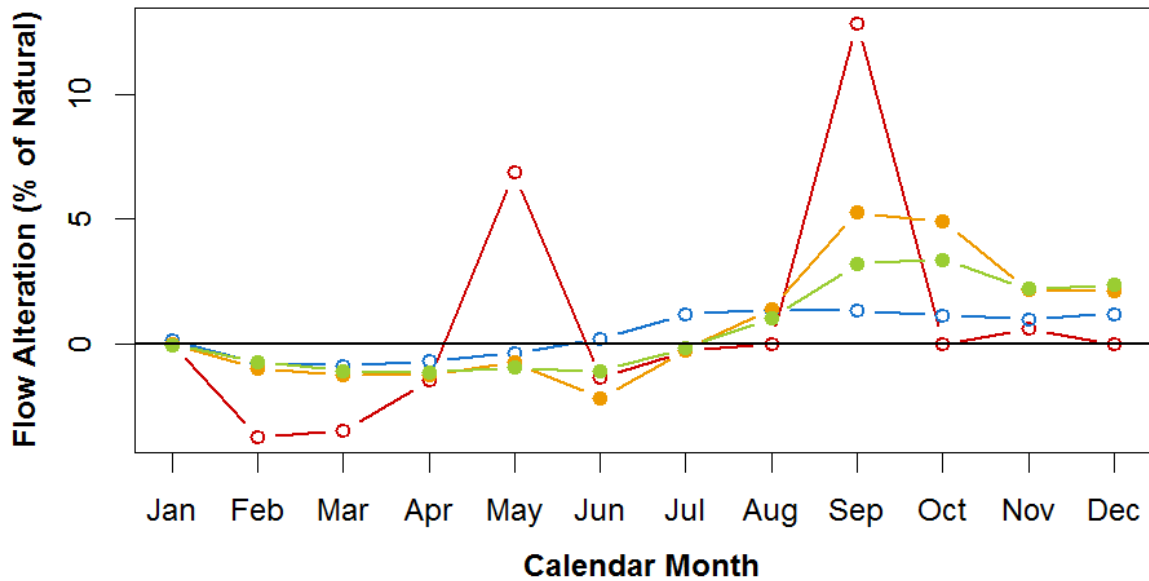


Figure A 33: Average monthly flow deviations from natural CRUISE flows at eco-nodes in the West Sub-Basin for the four tradeoff curve points of interest

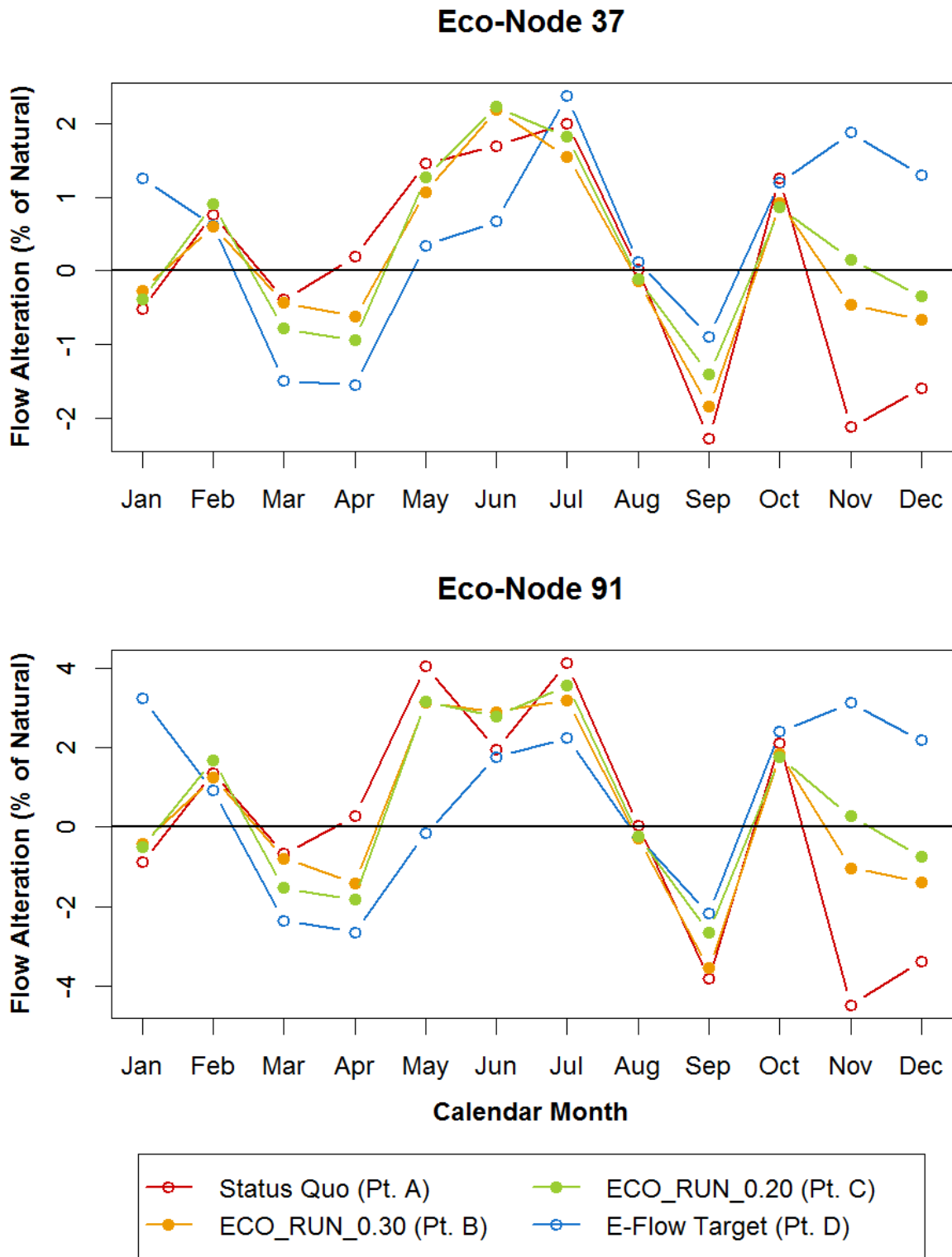


Figure A 34: Average monthly flow deviations from natural CRUISE flows at eco-nodes in the Ashuelot Sub-Basin for the four tradeoff curve points of interest