Characterization of the C-18 Basin Surface Water Hydrology 2007–2022 Using a Control Volume Method

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ACRONYMS, ABBREVIATIONS, AND UNITS OF MEASUREMENT

C&SF Project	Central and Southern Florida Flood Control Project
cfs	cubic foot (feet) per second
CV	control volume
DBHYDRO	South Florida Water Management District corporate environmental database
DBKEY	Database key for DBHYDRO
G-92$_{FC}$	water flowing through G-92 for flood control
G-92$_{WS}$	water flowing through G-92 for water supply
GWP	Grassy Waters Preserve
LD	Lainhart Dam
NWF	Northwest Fork
study period	October 14, 2007 through October 13, 2022

ABSTRACT

C-18 basin surface water outflows by source are estimated for the 15-year period from October 14, 2007 through October 13, 2022. A computational method of dividing the basin into discrete control volumes (CVs) having a conveyance (canal or river) bounded by water control structures is used to proportionally allocate inflows among outflows within each CV on a daily time step. C-18 basin inflows come from Grassy Waters Preserve (GWP) and rainfall. Basin outflows are discharged over Lainhart Dam (LD) and the S-46 water control structure. The average daily flow for this basin is 161 cubic feet per second (cfs), with a standard deviation of 191 cfs. LD discharges approximately two-thirds of the basin outflow. Approximately 60% of the LD flow is delivered to the Northwest Fork of the Loxahatchee River (NWF) through the G-92 structure. Although only 2% of LD flows originate from GWP, these flows make a positive impact on LD flows during dry times by increasing the amount of time LD flows are greater than 50 cfs by 4%, or 15 days per year, and increase the amount of time LD flows are greater than 35 cfs by 7%, or almost one month per year, on average. The median flow over LD during this study period is 28% higher than that from the 31-year period (1971–2001) that was studied to develop the minimum flow for the NWF.

INTRODUCTION

The C-18 basin includes approximately 100 square miles of land area upstream of Lainhart Dam (LD) and the S-46 water control structure in northern Palm Beach County. The basin is named for the Central and Southern Florida Flood Control Project (C&SF Project) canal that is the basin's primary surface water conveyance feature. The C-18 canal is an extension of the Southwest Fork of the Loxahatchee River, and its water surface elevations are controlled primarily by S-46. The C-18 canal and its water control structures provide flood protection, water supply, and water table maintenance. Water is supplied to the Northwest Fork of the Loxahatchee River (NWF) from the C-18 canal via the G-92 structure and South Indian River Water Control District canals. The C-18 basin has six major water control structures, which are shown in **Figure 1**:

- The S-46 gated spillway is an operable structure at the downstream terminus of the C-18 canal and discharges runoff into the Southwest Fork of the Loxahatchee River.
- LD is a fixed-crest weir on the NWF. Flows over this dam come from local runoff and inflows to the headwaters of the NWF from the G-92 water control structure.
- The G-92 water control structure discharges water from the C-18 canal to the C-14 canal then to the NWF. The structure is also capable of reverse flow, discharging runoff from the NWV sub-basin to the C-18 canal. G-92 was built by the South Florida Water Management District (SFWMD) and is not part of the C&SF Project system, hence the "G" designation.
- The C-18 water control structure is a steel sheet-pile weir located across the C-18W canal (Hungryland Slough Canal), on the northeast side of the SR 710 (Beeline Highway) bridge (B-45) crossing.
- The G-160 water control structure (a two-bay gated spillway) is located upstream of the bifurcation of the C-18 canal. The east-west leg is called the C-18W canal and the leg that extends south to the G-161 structure is called the C-18 extension. G-160 discharges surface water runoff from the sub-basin between G-160 and G-161 and water discharged from G-161.
- The G-161 water control structure allows surface water to flow from the City of West Palm Beach Water Catchment Area, also known as Grassy Waters Preserve (GWP), northward into the C-18 extension. The structure consists of a set of gated culverts that pass underneath Northlake Boulevard.

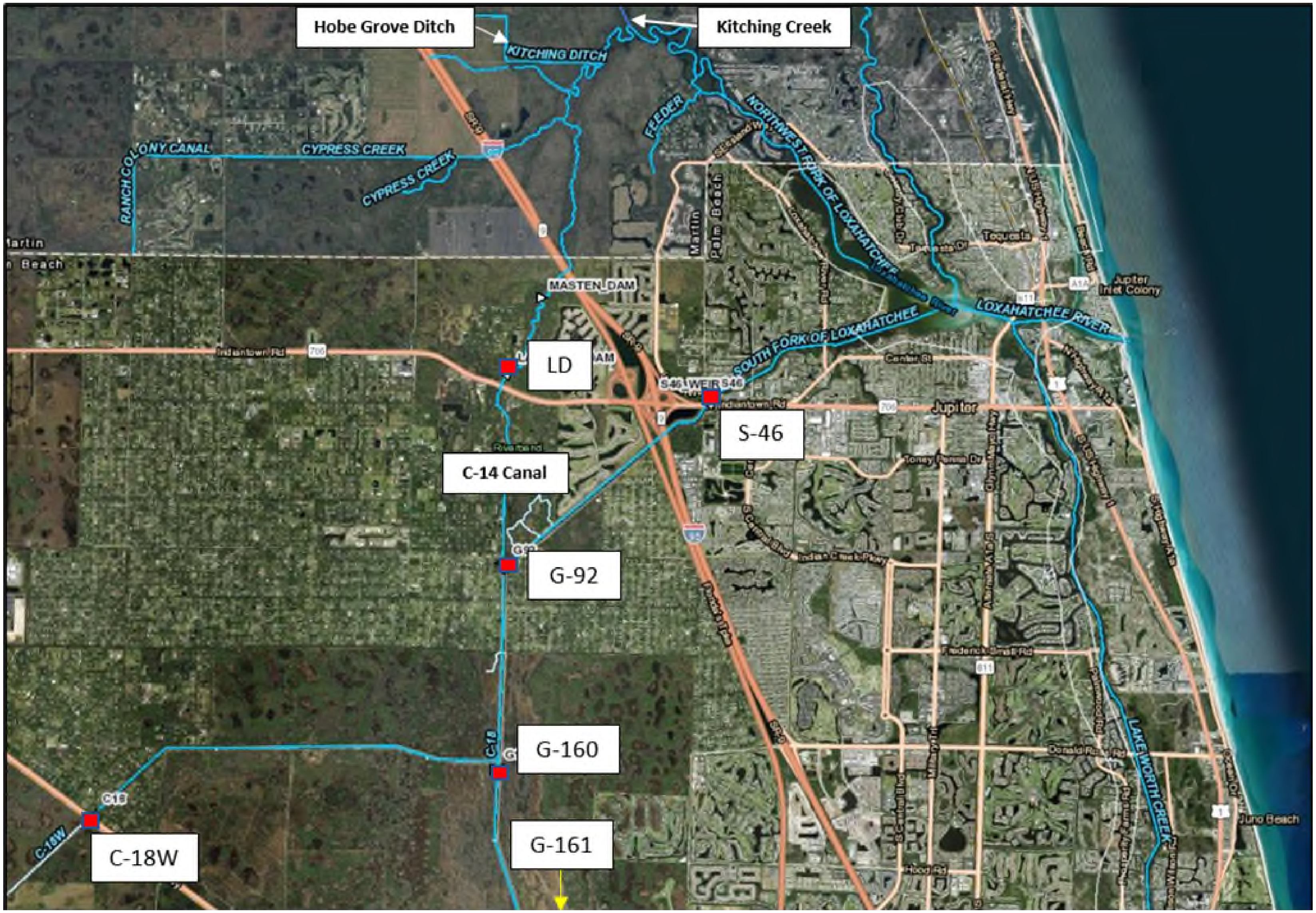

Figure 1. Map of the C-18 basin and water control structures. The G-161 structure is just below the bottom of the figure, south of G-160.

The C-18 basin receives inflows from rainfall-driven runoff and from GWP via G-161. The C-18 basin can be divided into four sub-basins:

- The NWF sub-basin is bound by the G-92 structure upstream and LD downstream. The conveyance feature is the C-14 canal that originates at G-92 and becomes the NWF before reaching LD. Surface water runoff from this sub-basin is discharged over LD.
- The C-18W sub-basin is upstream of the C-18 weir and has the C-18W canal as its conveyance feature.
- The C-18 sub-basin is bounded by the C-18 weir and G-160 upstream and G-92 and S-46 downstream. The conveyance features are the C-18 canal including the east-west extension to the C-18 weir.
- The G-16X sub-basin is bound by G-161 upstream and G-160 downstream. The C-18 canal extension is the conveyance feature, and it collects surface water runoff between the two structures.

A diagram of the C-18 basin, conveyance waterways (natural and constructed), and water control structures is shown in **Figure 2**. The black boxes denote water control structures, and the colored rectangles denote sub-basins or control volumes (CVs). In this analysis, GWP is not a control volume but is shown as the source for flows through G-161. **Figure 2** also shows average flows for water control structures and estimates of local runoff and unmeasured outflows from each sub-basin.

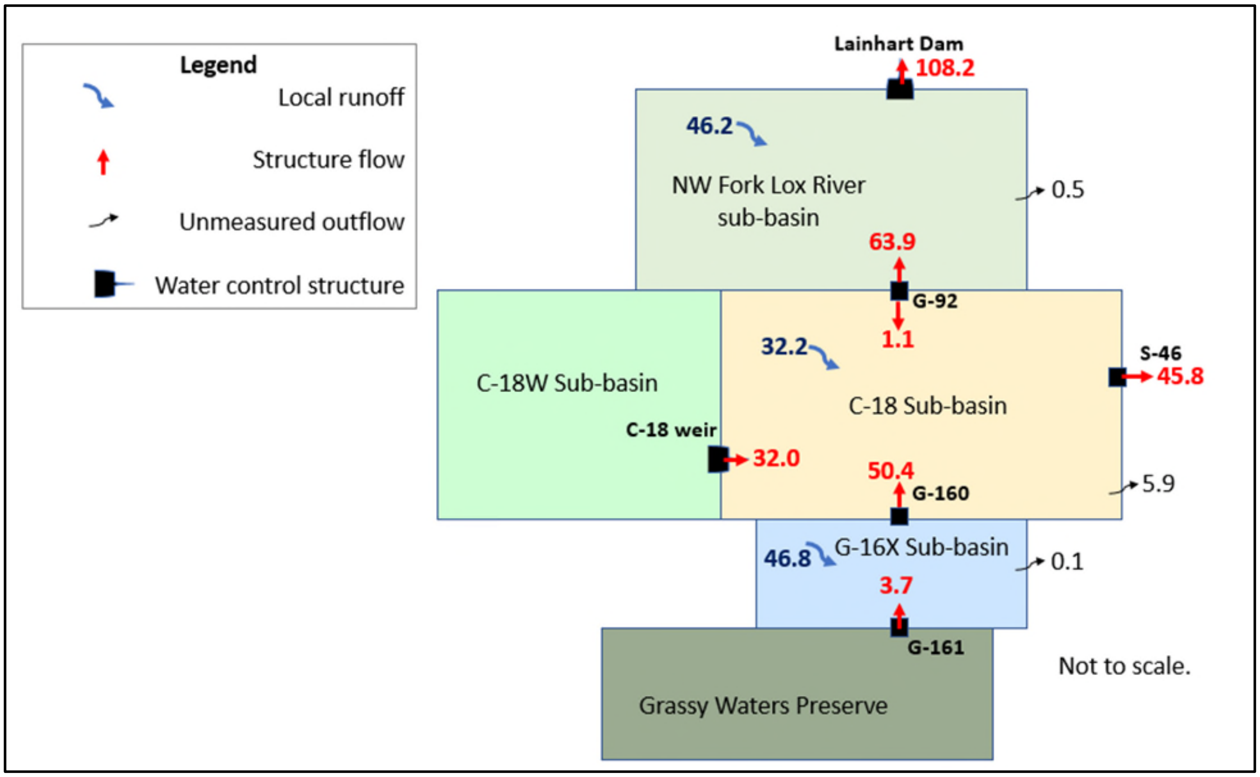

Figure 2. Diagram of the C-18 basin and subbasins (control volumes). Numbers are average flow rates in cubic feet per second (cfs). Inflows and outflows for each subbasin sum to nearly zero.

FLOW DATA

Average flows from the five structures for a continuous 15-year period (October 14, 2007–October 13, 2022; "study period") were created from data residing in the SFWMD's environmental corporate database DBHYDRO. The values used in this study can be accessed from DBHYDRO using the following DBKEYS: C-18 Weir (90870), G-161 (90909), G-160 (90908), G-92 (91279)[1], S-46 (91603); and Lainhart Dam (00295). **Table 1** summarizes information from the flow time series. Daily and seasonal flow rates and percentages vary substantially from the average flow values. The flow statistics for G-92 are reported separately for when it is flowing from C-18 to the NWF sub-basin, primarily for environmental water supply and for when flows are from the NWF sub-basin to C-18, primarily for flood control. To distinguish the operational modes, they are designated as G-92_{WS} and G-92_{FC}, respectively. G-92 was in water supply mode 92% of the time during this study period and in flood control mode 1% of the time. The structure was closed 7% of the time.

Table 1. Flow statistics for water control structures in the C-18 basin during the study period.

Statistic	G-161	G-160	C-18W	G-92_{WS}	G-92_{FC}	S-46	LD
Average flow, cfs	3.7	50	32	64	1.1	46	108
Median flow, cfs	0	25	4	44	67[a]	0	77
Maximum flow, cfs	194	1,107	463	261	514	2,078	749
Minimum flow, cfs	0	0	0	0	0	0	0
Time greater than 50 cfs							71%
Time greater than 35 cfs							88%
Time greater than 0 cfs	21%	74%	58%	92.5%	1%	30%	99.6%

INFLOWS

Table 2 lists average inflows to the C-18 basin conveyance network. Sources of inflows are GWP via G-161 and runoff from three sub-basins: (1) the drainage area between G-161 and G-160, (2) the drainage area bounded by G-160, G-92, and S-46, and (3) the drainage area bounded by LD and G-92. Total inflow to the basin averages 161 cfs or about 320 acre-feet per day. **Table 2** also lists the relative contribution of average inflow by source, expressed as percentages of total inflow.

Table 2. Average inflows and relative contributions to total inflow to the C-18 basin by source.

Source	Average Inflow (cfs)	Relative Contribution to Total Inflow
G-161 (from GWP)	3.7	2.3%
G-16X runoff	46.8	29.1%
C-18 weir flow	32.0	19.9%
C-18 runoff	32,1	20.0%
NWF runoff	46.2	28.7%
Total	**160.8**	**100.0%**

[1] As of this writing, the DBKEY for G-92 does contain correct values for days when flow went from the NWF basin to C-18. The author used DBKEY 64744 that has breakpoint data to calculate flow on such days. There were several days when flow through G-92 changed direction. The daily flow values in DBKEY 91279 are correct for these instances.

OUTFLOWS

Table 3 lists average outflows from the C-18 basin conveyance network. Outflow structures are LD, which discharges to the lower NWF, and S-46, which discharges to the Southwest Fork of the Loxahatchee River. Unmeasured outflows are the residual terms from daily mass balance calculations and are assumed to leave the basin by evaporation, groundwater seepage, or other unmeasured means.

Table 3. Average outflows and relative contributions to total outflow from the C-18 basin by structure.

Structure	Average Outflow (cfs)	Relative Contribution to Total Outflow
Lainhart Dam	108.2	67.3%
S-46	45.8	28.5%
Unmeasured	6.8	4.2%
Total	**160.8**	**100.0%**

CONTROL VOLUME METHOD

This method is used to estimate how inflows are distributed among outflows within a sub-basin by treating sub-basins as CVs. This method is documented in *Computing Estimates of FEB/STA Inflow Volumes as a Result of Lake Okeechobee Releases* (Sculley 2021) and is summarized here.

A CV is an area or canal segments defined by water control structures at the boundaries. Inflows to the CV are proportionally allocated among outflow structures of the CV daily according to the method described here.

First, inflows to and outflows from identified structures belonging to a CV (obtained directly from the best available data from sources such as DBHYDRO) are totaled as shown in **Equation 1**. Inflows and outflows to the primary canal system through secondary water control structures are not used in this calculation method primarily because these data are not readily available.

$$\boldsymbol{I_T} = \sum_{j=1}^{n} \boldsymbol{i_{j,t}} \text{ and } \boldsymbol{O_T} = \sum_{k=1}^{m} \boldsymbol{o_{k,t}} \tag{1}$$

In **Equation 1** above, I_T is the total inflow to a CV through n structures for time step t; $i_{j,t}$ is the inflow to the CV from water control structure j for time step t. Similarly, O_T is the total outflow from the CV through m structures for time step t; $o_{k,t}$ is the outflow from the CV from water control structure k for time step t.

If the total outflows are greater than or equal to the total inflows ($O_T \geq I_T$), then all inflows are distributed among the outflows and the difference is assumed to have been generated from within the CV from sources other than those used in this calculation method. The portion of outflow through structure o_1 that comes from inflow structure i_1 is the product of i_1 inflow and the proportion of o_1 to total outflow:

$$\boldsymbol{o_{1,1}}(\boldsymbol{O_T} \geq \boldsymbol{I_T}) = \boldsymbol{i_1} * \frac{\boldsymbol{o_1}}{\boldsymbol{O_T}} \tag{2a}$$

If total outflows are less than total inflows ($O_T < I_T$), then all outflows are assigned among inflows; the difference is assumed to be due to unaccounted outflows. The portion of outflow through structure o_1 that comes from inflow structure i_1 in this case is the product of o_1 outflow and the proportion of i_1 to total inflow:

$$\boldsymbol{o_{1,1}(O_T < I_T) = o_1 * \frac{i_1}{I_T}} \quad \textbf{(2b)}$$

Equations (2a) and **(2b)** can be combined to calculate $o_{1,1}$ for all inflow-outflow conditions:

$$\boldsymbol{o_{1,1} = min\left[\frac{i_1 * o_1}{I_T}, \frac{i_1 * o_1}{O_T}\right] = \frac{i_1 * o_1}{max[I_T, O_T]}} \quad \textbf{(2c)}$$

The general form of **Equation (2c)**, the portion of flow from inflow structure $i_{j,t}$ that exits the CV through outflow structure $o_{k,t}$ for time step t is represented as $o_{k,t,j}$ and computed as follows:

$$\boldsymbol{o_{k,t,j} = \frac{i_{j,t} * o_{k,t}}{\max[I_T, O_T]}} \quad \textbf{(3)}$$

Measured inflows at structures are distributed among measured outflows for each CV on a daily time step. When total outflows are greater than total inflows, the difference is attributed to local runoff. If total inflows exceed total outflows, the difference is assumed to have exited the CV by unmeasured means (e.g., evapotranspiration, groundwater seepage). Surface water storage in the CV is not calculated. The total amount of water, however, can be estimated (see example in the *CV-1: G-16X Sub-basin* section below).

CV-1: G-16X SUB-BASIN

This CV has one inflow structure (G-161) and one outflow structure (G-160). The time series from these two structures and the CV method are used to estimate contributions of flow to G-160 from G-161 and local runoff from the G-16X sub-basin. Not all G-161 flows (3.7 cfs shown in **Table 1**) are discharged through G-160 (3.6 cfs shown in **Table 4**). This residual (0.1 cfs) is the result of days when G-161 inflows exceed G-160 outflows. This flow is assumed to exit the CV by unmeasured means.

Table 4. CV-1 mass balance (inflows and outflows).

Inflows	Outflow	
	G-160 (cfs)	Relative Contribution
G-161	3.6 [a]	7.1%
G-16X sub-basin runoff	46.8	92.9%
Total	50.4	100.0%

a. Since G-161 inflow was 3.7 cfs, 0.1 cfs is estimated to have exited the CV by unmeasured means.

CV-2: C-18 SUB-BASIN

This CV has three inflow structures (G-160, C-18W, and G-92$_{FC}$) and two outflow structures (G92$_{WS}$ and S-46). The time series from these structures and the CV method are used to estimate contributions of flow to G-92 and S-46 from G-160, the C-18 weir, and local runoff from the C-18 sub-basin. G-160 flow contributions to both structures can be further broken down to those originating from G-161 and G-16X sub-basin runoff. **Table 5** shows the estimated contributions to outflow structures G-92 and S-46. Not all structure inflows were accounted for in structure outflows. Approximately 3 cfs each from G-160 and the C-18 weir were estimated to have left the CV unmeasured.

Table 5. CV-2 mass balance (inflows and outflows).

Inflows	Outflows			
	$G\text{-}92_{WS}$ (cfs)	**Relative Contribution at G-92**	**S-46 (cfs)**	**Relative Contribution at S-46**
G-160	25.2	39.5%	22.1	48.1%
C-18W	15.0	23.4%	14.1	30.9%
$G\text{-}92_{FC}$	0.0	0.0%	1.1	2.5%
C-18 runoff	23.7	37.1%	8.5	18.5%
Total	**63.9**	**100.0%**	**45.8**	**100.0%**

CV-3: NORTHWEST FORK (NWF) SUB-BASIN

This CV has one inflow structure ($G\text{-}92_{WS}$) and two outflow structures (LD and $G\text{-}92_{FC}$). The time series from these two structures and the CV method are used to estimate contributions of flow to LD from G-92 and local runoff from the NWF sub-basin. LD flows from G-92 can be further broken down to those from G-161, G-16X sub-basin runoff, and C-18 sub-basin runoff. **Table 6** shows nearly 60% of LD flows originate upstream of G-92. **Table 7** lists G-92 flows over LD by the four sources. It shows the estimated contribution of LD flows from GWP (G-161) is small but efficient. Nearly two-thirds of flows discharged from GWP via G-161 arrive at LD (2.4 of 3.7 cfs). The next section will present the effect of these flows have had on LD flows being above certain threshold.

Table 6. CV-3 inflows and structure outflows.

Inflows	Outflows			
	Lainhart Dam (cfs)	**Relative Contribution**	**$G\text{-}92_{FC}$**	**Relative Contribution**
$G\text{-}92_{WS}$	63.4	58.6%	0.0	0%
NWF runoff	44.8	41.4%	1.1	100%
Total	**108.2**	**100.0%**	**1.1**	**100%**

Table 7. $G\text{-}92_{WS}$ flows by source.

Inflows	Outflow	
	Lainhart Dam (cfs)	**Relative Contribution**
C-18 runoff	23.5	21.7%
C-18 Weir	14.9	13.8%
G-16X runoff	22.6	20.9%
G-161	2.4	2.2%
Total	**63.4**	**58.6%**

Table 8 summarizes flows throughout the entire CV network. The upper and lower halves of the table list the total average flow and relative contribution to each water control structure by source. For example, the average flow at G-161 for the period of record is 3.7 cfs; nearly all this flow passes through G-160 (3.6 cfs) and this amount contributes 7% to the total G-160 flow. The 0.1-cfs difference is estimated as an unmeasured outflow. After G-160, 2.5 cfs (69% of 3.6 cfs) is discharged through G-92, 0.9 cfs (25%) is discharged through S-46, and 0.2 cfs (6%) is estimated as unmeasured outflow. Finally, 2.4 cfs or 96% of the G-161 flow that was discharged through G-92 was also discharged over LD. Most often G-161 is opened to supplement flows over LD and water managers coordinate this operation with concurrent openings and closures to maximize the likelihood of this outcome. Although the average flow rate through G-161 is small when expressed as a percentage of basin outflows (~2%), 65% (2.4 cfs) reaches LD. The lower half of **Table 8** shows the relative contribution to structure flow by source.

Table 8. Total average structure flows and relative contributions by source.

Source	Structure Flow (cfs)						
	G-161	**C-18W**	**G-160**	**$G92_{FC}$**	**$G\text{-}92_{WS}$**	**S-46**	**LD**
Grassy Waters Preserve	3.7	0.0	3.6	0.0	2.5	0.9	2.4
C-18W sub-basin runoff	0.0	32.0	0.0	0.0	15.0	14.1	14.9
G-161X sub-basin runoff	0.0	0.0	46.8	0.0	22.8	21.2	22.6
C-18 sub-basin runoff	0.0	0.0	0.0	0.0	23.7	8.5	23.5
NWF sub-basin runoff	0.0	0.0	0.0	1.1	0.0	1.1	44.8
Total	**3.7**	**32.0**	**50.4**	**1.1**	**63.9**	**45.8**	**108.2**
	Relative Contribution						
Grassy Waters Preserve	100%	0%	7%	0%	4%	2%	2%
C-18W sub-basin runoff	0%	100%	0%	0%	23%	31%	14%
G-161X sub-basin runoff	0%	0%	93%	0%	36%	46%	21%
C-18 sub-basin runoff	0%	0%	0%	0%	37%	19%	22%
NWF sub-basin runoff	0%	0%	0%	100%	0%	2%	41%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

LAINHART DAM FLOW STATISTICS

Average flow over LD during the study period was 108 cfs. The median (50th percentile) flow was 77 cfs. Two threshold flow values, 35 and 50 cfs, are of interest as the former is a threshold for the minimum flow that is required for the minimum flow and minimum water level (MFL) for the NWF measured at LD, and the latter is the flow SFWMD attempts to deliver to LD when sufficient regional water is available[2]. LD flows were less than 35 cfs 12% of the time (about 45 days per year) and less than 50 cfs 29% of the time (about 105 days per year), respectively.

Local runoff from the NWF sub-basin contributed 41% (45 cfs) to the total LD flow; inflow from G-92 contributed the remaining 59% (63 cfs). Without inflows from G-92, LD flows would have lessened significantly; flows less than 35 cfs would have occurred 54% of the time (about 197 days per year) and flows less than 50 cfs would have increased to 71% of the time (about 106 days per year). See **Table 9**.

G-161 discharged an average of 4 cfs during the study period. Excluding days when the structure was closed (about 72% of the time), the average flow was 17 cfs. Although G-161 discharge is comparatively small to that of other structures and runoff, delivery of its flows to the intended destination (LD) was efficient (65%). The flow contribution to LD originating from G-161 was enough to decrease the percentage of time LD flow was below 50 cfs by about 15 days per year (from 33 to 29% of the time) and increase the LD flow below 35 cfs by about 26 days per year (from 19 to 12% of the time).

Table 9. Lainhart Dam statistics for total flow, local runoff only, and excluding flow originating from the G-161 water control structure.

Lainhart Dam Flow	Average (cfs)	Median (50th Percentile) (cfs)	Time ≥ 50 cfs	Time ≥ 35 cfs
Total	108	77	71%	88%
Local Runoff Only (Excludes G-92 Inflow)	45	31	29%	46%
Excluding Flow from G-161 Only	106	77	67%	81%

Figure 3 compares the flow duration curve for LD for the study period (2007–2022) with data from a flow frequency analysis of the period 1971–2001 documented in the final draft of the *MFLs for the Northwest Fork of the Loxahatchee River*[3] (SFWMD 2002). The median LD flow during the study period (77 cfs) is 17 cfs higher than from the 1971–2001 period (60 cfs). LD flows above 35 cfs during the study period were also higher (89% of the time) compared to the 1971–2001 period (approximately 63%). Similarly, LD flows above 50 cfs increased from approximately 54 to 71%.

[2] *2018 Lower East Coast Water Supply Plan Update*, Appendix C, page C-20 (SFWMD 2018).

[3] Figure 20, Flow Duration Curve for the Lainhart Dam 1971–2001, page 107.

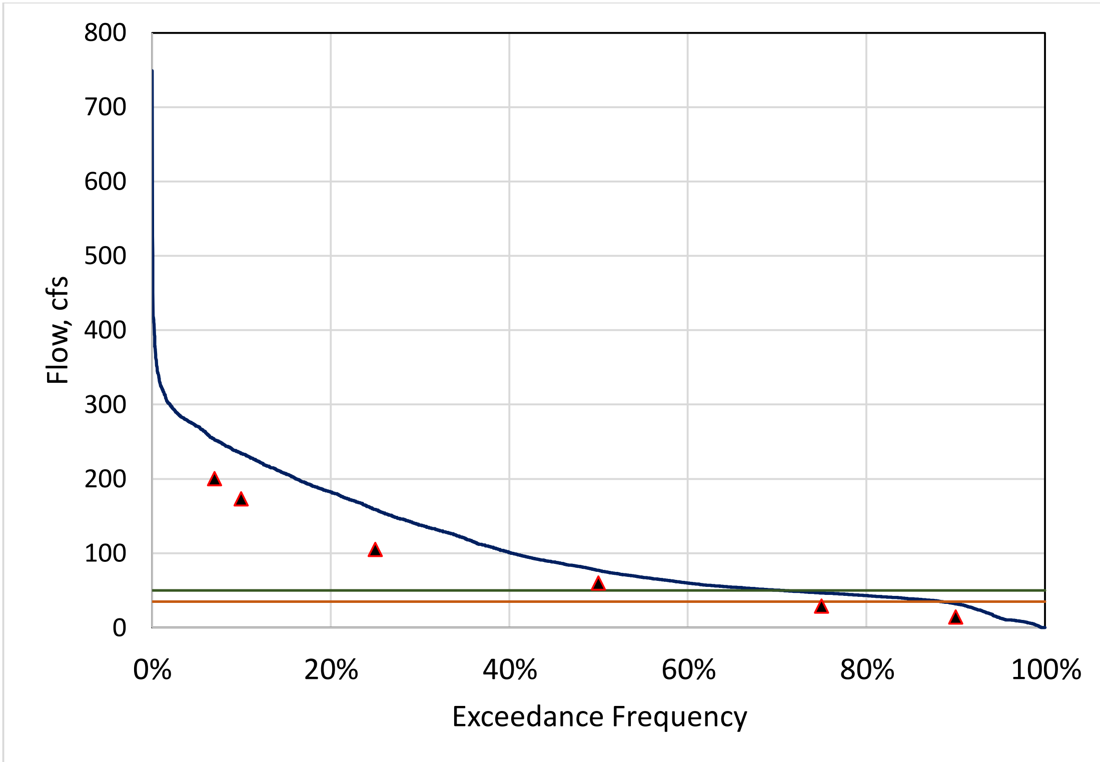

Figure 3. Lainhart Dam flow frequency curves from 1971–2001 (triangles) and 2007–2022 (black line). Horizontal lines reference 35 and 50 cfs.

MINIMUM FLOW EXCEEDANCES

During the study period, the NWF experienced seven exceedances of the minimum flow criterion. An exceedance occurs when flow over LD declines below 35 cfs for more than 20 consecutive days[4]. Using the CV method, contributions to flow from G-92 reduced the number of exceedances from 33 to seven. In other words, had LD only received flow from local runoff, there would have been 33 exceedances. Furthermore, LD flows that originated from G-161 alone reduced the number of exceedances by two (from nine to seven). **Figure 4** shows LD flows from local runoff and from G-92 during the study period. Instances where the blue bar is higher than the 35 cfs threshold are when supplemental flows from outside the NWF sub-basin were enough to sustain the 35 cfs flow rate at LD.

[4] Rule 40E-8.221 (4) (c) 1.

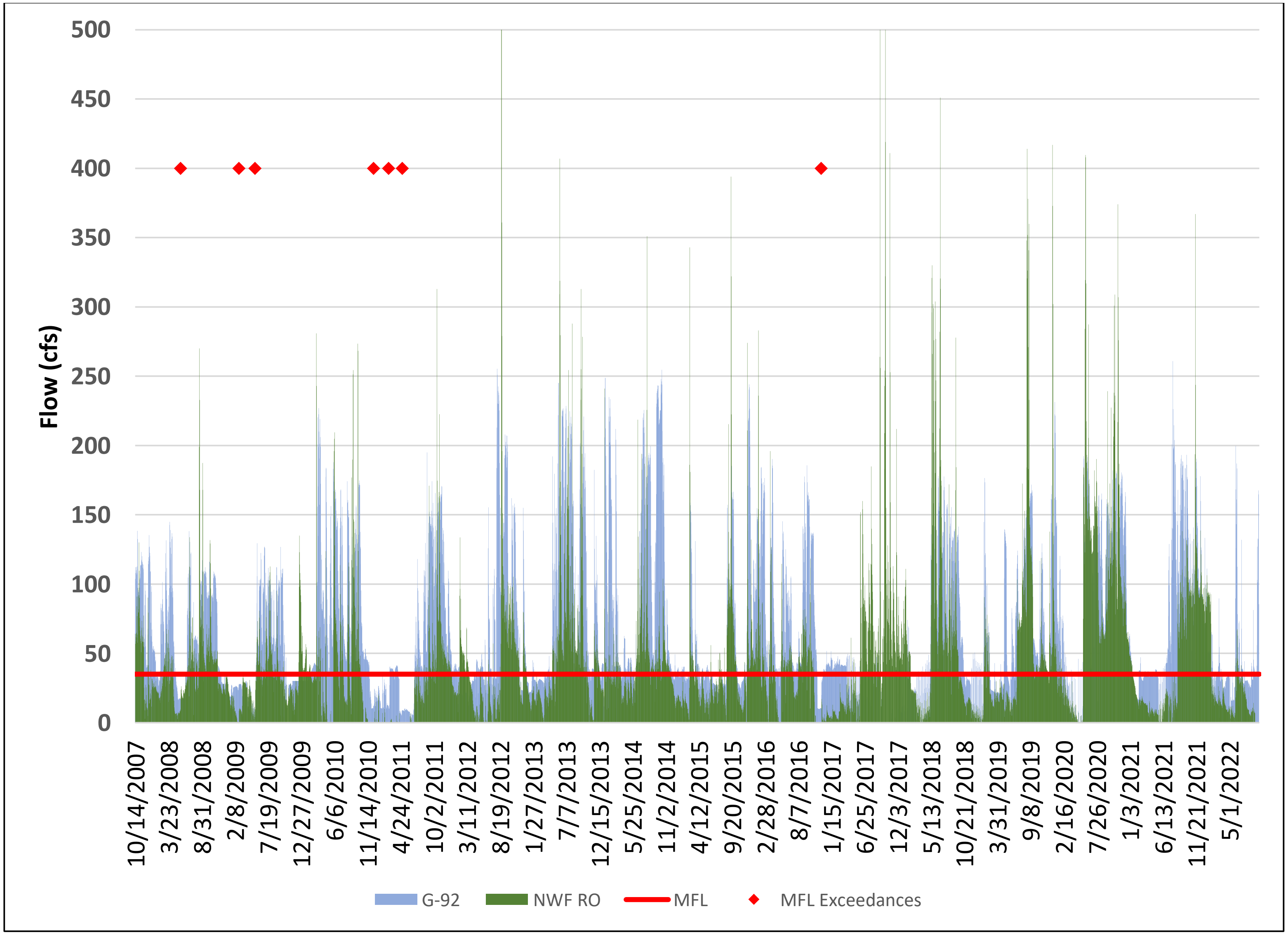

Figure 4. Stacked bar chart of Lainhart Dam flows by primary source. MFL exceedances are shown with diamond symbols. Vertical axis is truncated at 500 cfs to enhance clarity at lower flows.

EFFECT OF FLOWS FROM G-92

Not only did the G-92 flows reduce the number of exceedances by almost 80%, but also reduced the number of days LD flows were in exceedance by 95% and shortened the average duration of exceedance from 52 days to 12 days (**Table 10**). In these calculations, G-92 flows are from all sources, including flows from G-161.

Table 10. Comparison of observed MFL performance with those of hypothetical scenarios that exclude flow sources from G-92 and G-161.

MFL Performance Statistics	Observed	Without Flow from G-92	Without Flow from G-161
Number of exceedances	7	33	9
Number of days in exceedance mode	84	1,702	235
Average number of days per year in exceedance mode	6	113	16
Average exceedance duration, days	12	52	26

EFFECT OF FLOWS FROM G-161

The CV method also estimates that flows originating from G-161 also reduced the frequency and duration of MFL exceedances at LD. These flows reduced the number of exceedances by 2, reduced the time LD flows were in exceedance by 63%, and shortened the average duration of exceedance by 54% (**Table 10**).

Figure 4 shows LD flows from local runoff and from G-92 during the study period. Instances where the blue bar is higher than the 35-cfs threshold are when supplemental flows from outside the NWF sub-basin were enough to sustain the 35-cfs flow rate at LD. **Figure 5** similarly shows times when LD flow originating from G-161 was sufficient to sustain at least 35 cfs over LD (flows in red). This occurred for 151 days of the 15-year study period.

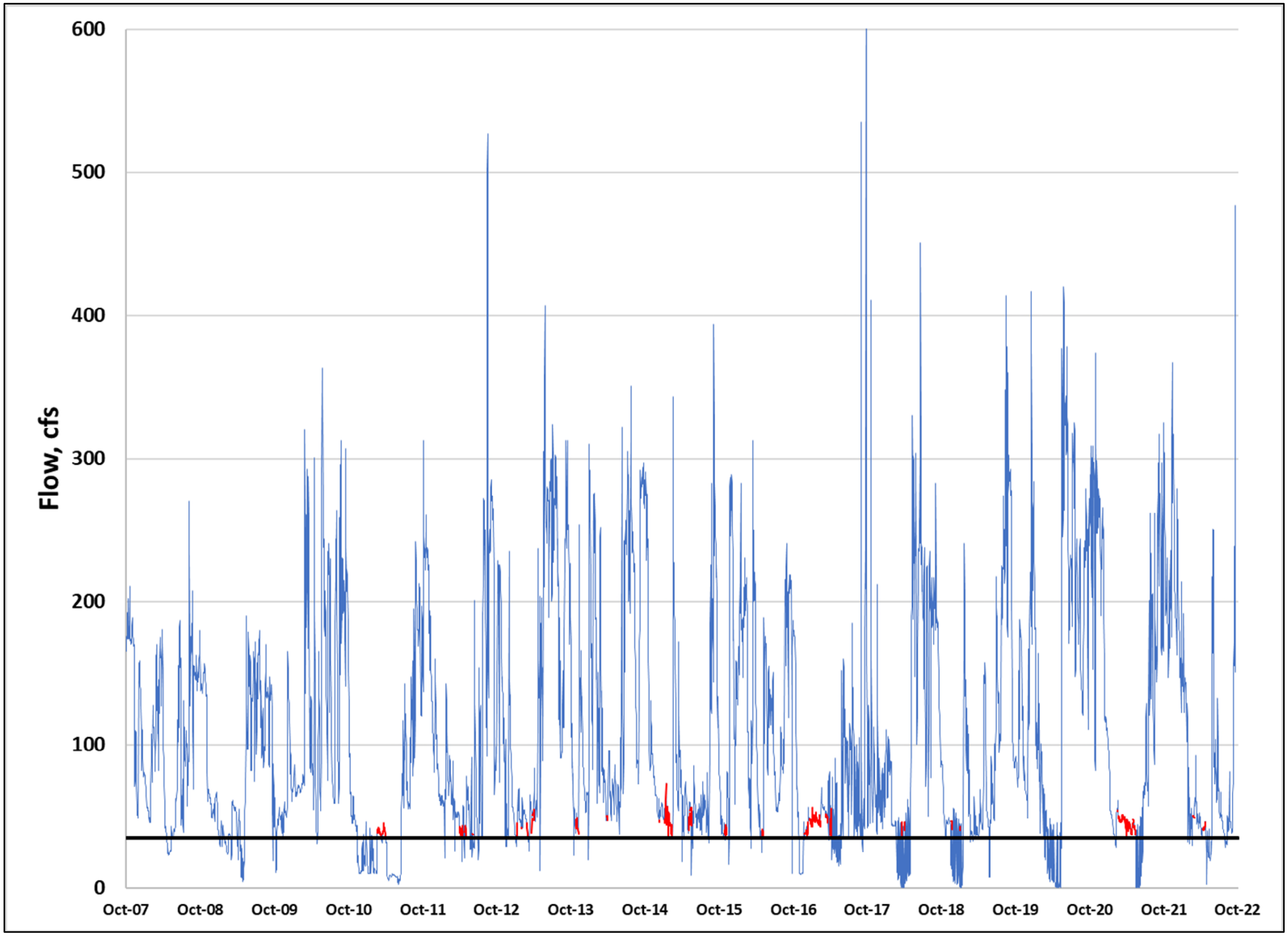

Figure 5. Lainhart Dam flow hydrograph (blue) with times when flow originating from G-161 raised the total flow over Lainhart Dam to 35 cfs or greater (red). Vertical axis is truncated at 600 cfs to enhance clarity at lower flows.

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