In [4]:
```
using DataFrames, Plots, Statistics, JSON, Clp
plotlyjs()
include(joinpath(dirname(pwd()),"src/TuLiPa.jl")); # using Dates, JuMP, HiGHS, CSV, Cluste
```

Demo 4 - Deterministic hydro

Demo 4 optimizes the Aurland watercourse against an exogen area. NVEs dataset for the hydropower system in 2022 is open, but we have not published datasets for 2025/2030/2040/2050 since it would reveal investment plans. The dataset exist in several formats:

- Aggregated (for Res and RoR) production capacity, reservoir capacity, inflow and inflow profiles per price areas from https://www.nve.no/energi/analyser-og-statistikk/vaerdatasett-for-kraftsystemmodellene/
- Detailed watercourse descriptions from https://www.nve.no/energi/energisystem/vannkraft/modell-av-det-norske-vannkraftsystemet/. The dataset exist in two DETD-formats (per EMPS area (also includes rest modules for small-scale hydro) or per watercourse), and simplified in an Excel-format. The dataset used in this demo is derived from the excel-format with some differences:
  - Every water balance has its own module (i.e. a module with both regulated and unregulated inflow is split into two modules).
  - It has pq-kurves and environmental restrictions
- The inflow series for the detailed dataset can be found at https://www.nve.no/vann-og-vassdrag/hydrologiske-data/historiske-data/historiske-vannfoeringsdata-til-produksjonsplanlegging/.

The price for the exogen area is generated in 1.6 in Demo 2.

Special model objects are used for the detailed hydropower modelling. These are SoftBound (for reservoir, release or bypass restrictions) and SegmentedArrow (for release PQ-kurves).

Function to add boundary condition for storages

In [2]:
```
# The hydropower storages in the dataset needs boundary conditions for the state variables
function addStartEqualStopAllStorages!(modelobjects)
    for obj in values(modelobjects)
        if obj isa BaseStorage
            trait = StartEqualStop(obj)
            modelobjects[getid(trait)] = trait
        end
    end
end
```

Out[2]:
```
addStartEqualStopAllStorages! (generic function with 1 method)
```

Solve and plot results for watercourse scenarios

We solve the Aurland watercourse deterministically for 10 scenarios that last 5 years each, against a price series generated in 1.7 in Demo 2. The hydro horizon is with a weekly resolution and the power horizon with a daily resolution.

Results:

- We get expected behaviour with water being stored from the spring flood to the winter, and most production in the winter.
- Releases, pumping, spill, bypass and storages are restricted by their upper capacity, and environmental restrictions.
- For pumped hydro storage there is not production and pumping at the same time.
- With these horizons the problems are very fast to build, update, solve and plot. Other setting not shown in this demo:
  - With a hourly resolution in the power horizon, it takes around 1 s to build the problem, 0.2 s to update each scenario and 2 s to solve each scenario.
  - The HiGHS dual simplex solver is much faster than the interior-point method solver.

Most of the code below is for collecting and plotting results. Scroll down for plots.

In [3]:
```
# Make list of scenarios
function getscenarios(dt; years)
    [TwoTime(getisoyearstart(dt), getisoyearstart(yr)) for yr in years]
end

function runwatercourse()

    # Read dataelements from json-files
    sti_dynmodelldata = "dataset_vassdrag"
    price = JSON.parsefile("priceDMK.json")
    detdprice = getelements(price);
    tidsserie = JSON.parsefile(joinpath(sti_dynmodelldata, "tidsserier_detd.json"))
    detdseries = getelements(tidsserie, sti_dynmodelldata);
    dst = JSON.parsefile(joinpath(sti_dynmodelldata, "dataset_detd_AURLAND_H.json"))
    detdstructure = getelements(dst);

    elements = vcat(detdseries,detdprice,detdstructure)

    # Add horizons to the dataset
    scenarioyearstart = 1981
    scenarioyearstop = 1996 # price series only goes to 1995
    hydro_horizon = SequentialHorizon(13*5, Hour(168*4))
    power_horizon = SequentialHorizon(7*52*5, Hour(24))
    push!(elements, getelement(COMMODITY_CONCEPT, "BaseCommodity", "Power",
            (HORIZON_CONCEPT, power_horizon)))
    push!(elements, getelement(COMMODITY_CONCEPT, "BaseCommodity", "Hydro",
            (HORIZON_CONCEPT, hydro_horizon)))

    # Select which scenarios to include from the time-series
    push!(elements, getelement(TIMEPERIOD_CONCEPT, "ScenarioTimePeriod", "ScenarioTimePeri
            ("Start", getisoyearstart(scenarioyearstart)), ("Stop", getisoyearstart(scenar

    # Add an exogenous price area that the plants and pumps can interact with. All units ar
    push!(elements, getelement(BALANCE_CONCEPT, "ExogenBalance", "PowerBalance_NO5",
            (COMMODITY_CONCEPT, "Power"),
            (PRICE_CONCEPT, "PriceDMK")))

    # Generate modelobjects from dataelements and add boundary conditions to storages
    modelobjects = getmodelobjects(elements)
    addStartEqualStopAllStorages!(modelobjects)

    # List all plants, pumps, bypasses, spills and storages - and plant arrows to calculate
    plants = []
    pumps = []
    bypasspills = []
    storages = []

    plantarrows = []
    demandarrows = []

    for obj in values(modelobjects)
        if obj isa BaseFlow
```

```
            for a in getarrows(obj)
                balance = getbalance(a)
                if balance isa ExogenBalance
                    if isingoing(a)
                        push!(plants,obj)
                        push!(plantarrows,a)
                    else
                        push!(pumps,obj)
                        push!(demandarrows,a)
                    end
                    @goto skip
                end
            end
            push!(bypasspills, obj)
        end
        @label skip
        if obj isa BaseStorage
            push!(storages,obj)
        end
    end

    # Periods in horizons
    numperiods_power = getnumperiods(power_horizon)
    numperiods_hydro = getnumperiods(hydro_horizon)

    # Timefactors to convert results regardless of horizon (Mm3 -> m3/s and GWh -> MWh/h)
    timedelta_power = gettimedelta(power_horizon,1)
    timedelta_hydro = gettimedelta(hydro_horizon,1)
    timefactor_power = getduration(timedelta_power)/Millisecond(3600000000)
    timefactor_hydro = getduration(timedelta_hydro)/Millisecond(1e9)

    # Choose scenarios model year 2021 and weather scenarios starting from 1981/1982/1983 e
    scenarios = getscenarios(2021; years=1981:1990)

    # Preallocate matrices to store results
    production = zeros(numperiods_power, length(scenarios), length(plants))
    consumption = zeros(numperiods_power, length(scenarios), length(pumps))
    hydrolevels = zeros(numperiods_hydro, length(scenarios), length(storages))
    bypasspill = zeros(numperiods_hydro, length(scenarios), length(bypasspills))

    # Initialize problem, update for chosen scenario and collect results
    @time prob = HiGHS_Prob(collect(values(modelobjects)))

    for (s, t) in enumerate(scenarios)
        scenyear = string(getisoyear(getscenariotime(t)))

        @time update!(prob, t)

        @time solve!(prob)
        println("Objective value in scenario $(s): ", getobjectivevalue(prob))

        # Store results for each scenario
        for j in 1:numperiods_power

            # Production
            for i in 1:length(plants)
                arrow = plantarrows[i]
                if arrow isa SegmentedArrow # PQ-kurve
                    production[j, s, i] = 0
                    for k in 1:length(getconversions(arrow))
                        segmentid = getsegmentid(arrow, k)
                        horizon = gethorizon(arrow)
                        conversionparam = getconversions(arrow)[k]
                        querytime = getstarttime(horizon, j, t)
                        querydelta = gettimedelta(horizon, j)
                        conversionvalue = getparamvalue(conversionparam, querytime, queryd
                        production[j, s, i] += getvarvalue(prob, segmentid, j)*conversionv
                    end
                else
```

```
                horizon = gethorizon(arrow)
                conversionparam = _getcontributionparam(arrow)
                querytime = getstarttime(horizon, j, t)
                querydelta = gettimedelta(horizon, j)
                conversionvalue = getparamvalue(conversionparam, querytime, querydelta
                production[j, s, i] = getvarvalue(prob, getid(plants[i]), j)*conversio
            end
        end

        # Pump consumption
        for i in 1:length(pumps)
            arrow = demandarrows[i]
            horizon = gethorizon(arrow)
            conversionparam = _getcontributionparam(arrow)
            querytime = getstarttime(horizon, j, t)
            querydelta = gettimedelta(horizon, j)
            conversionvalue = getparamvalue(conversionparam, querytime, querydelta) #
            consumption[j, s, i] = getvarvalue(prob, getid(pumps[i]), j)*conversionval
        end
    end
    for j in 1:numperiods_hydro

        # Storage levels
        for i in 1:length(storages)
            hydrolevels[j, s, i] = getvarvalue(prob, getid(storages[i]), j)
        end

        # Bypass and spill
        for i in 1:length(bypasspills)
            bypasspill[j, s, i] = getvarvalue(prob, getid(bypasspills[i]), j)/timefact
        end
    end
end

# Plot list of yearly mean production and demand for each supply/demand
supplynames = [getinstancename(getid(plant)) for plant in plants]
demandnames = [getinstancename(getid(pump)) for pump in pumps]
meandemand = dropdims(mean(consumption[:,:,:],dims=(1,2)),dims=(1,2))
meanproduction = dropdims(mean(production[:,:,:],dims=(1,2)),dims=(1,2))
supplydf = sort(DataFrame(Supplyname = supplynames, Yearly_supply_GWh = meanproduction
demanddf = sort(DataFrame(Demandname = demandnames, Yearly_demand_GWh = meandemand*8.7
supplydf[!,:ID] = collect(1:length(supplynames))
demanddf[!,:ID] = collect(1:length(demandnames))
joineddf = select!(outerjoin(supplydf,demanddf;on=:ID),Not(:ID))
show(joineddf,allcols=true, allrows=true)

# Start of weather scenario for plot labels
scenyears = reshape([string(getisoyear(getscenariotime(t))) for t in scenarios],1,leng

# Useful lists of modelobjects
mainobjects = getmainmodelobjects(modelobjects)
balanceflows = getbalanceflows(modelobjects)

# Preallocate to store environmental restrictions
softvalues_power = zeros(numperiods_power)
softvalues_hydro = zeros(numperiods_hydro)

# For each plant plot its production, and connected pumping, storage, spill and bypass
for i in 1:length(plants)

    # Plot production
    plant = plants[i]
    plot1 = plot(sum(production[:,:,i],dims=3),label=scenyears, linewidth=0.5, ylabel=
    plot!(plot1, mean(sum(production[:,:,i],dims=3),dims=2),name="Mean", linewidth=5,

    # Release restrictions
    if haskey(mainobjects,plant)
        for trait in mainobjects[plant]
            if trait isa BaseSoftBound
```

```
                # Convert release restriction to MWh/h to plot it together with the pr
                # TODO: Now assume constant conversion
                arrow = plantarrows[i]
                horizon = gethorizon(arrow)
                dummytime = ConstantTime()
                dummydelta = MsTimeDelta(Hour(1))

                if arrow isa SegmentedArrow # PQ-curve
                    # TODO: Use mean energy equivalent rather than calculating it
                    conversionvalue = 0
                    capacitytotal = 0
                    for k in 1:length(getconversions(arrow))
                        conversionparam = getconversions(arrow)[k]
                        capacityparam = getcapacities(arrow)[k]
                        capacityvalue = getparamvalue(capacityparam, dummytime, dummyd
                        if getparamvalue(conversionparam, dummytime, dummydelta) > 0
                            conversionvalue += getparamvalue(conversionparam, dummytim
                            capacitytotal += capacityvalue
                        end
                    end
                    conversionvalue /= capacitytotal
                else
                    conversionparam = getconversion(arrow)
                    conversionvalue = getparamvalue(conversionparam, dummytime, dummyd
                end

                for j in 1:numperiods_power
                    softvalues_power[j] = getrhsterm(prob, getleid(trait), getsoftcapi
                end
                if sum(softvalues_power) > 0
                    plot!(plot1, softvalues_power,name="MaxSoftCap")
                elseif sum(softvalues_power) < 0
                    plot!(plot1, softvalues_power*-1,name="MinSoftCap")
                end
            end
        end
    end
    allplots = []
    push!(allplots,plot1)

    # Pumped power - if arrows of plant and pump is connected to the three same balance
    arrows = getarrows(plant)
    balances = []
    if length(arrows) == 3
        for arrow in arrows
            push!(balances, getbalance(arrow))
        end
    end

    for (i, pump) in enumerate(pumps)
        arrows = getarrows(pump)
        if length(arrows) == 3
            if (getbalance(arrows[1]) in balances) & (getbalance(arrows[2]) in balance

                # Plot pump demand
                plot4 = plot(sum(consumption[:,:,i],dims=3),label=scenyears, ylabel="M
                plot!(plot4, mean(sum(consumption[:,:,i],dims=3),dims=2),name="Mean",
                push!(allplots, plot4)
                filter!(e -> e != pump, pumps)
            end
        end
    end

    # Main reservoir - search upwards in the watercourse for reservoir connected to th
    arrows = getarrows(plant)
    for arrow in arrows
        if !isingoing(arrow)
            prodbalance = getbalance(arrow) # first identify water balance over plant
```

```
                # plants with only regulated inflow have one storage directly over plant /
                for (i, storage) in enumerate(storages)
                    if getbalance(storage) == prodbalance

                        # Plot identified reservoir
                        plot2 = plot(sum(hydrolevels[:,:,i],dims=3),label=scenyears, linew
                        plot!(plot2, mean(sum(hydrolevels[:,:,i],dims=3),dims=2),name="Mea

                        # Plot reservoir restrictions
                        if haskey(mainobjects,storage)
                            for trait in mainobjects[storage]
                                if trait isa BaseSoftBound
                                    for j in 1:numperiods_hydro
                                        softvalues_hydro[j] = getrhsterm(prob, getleid(tra
                                    end
                                    if sum(softvalues_hydro) > 0
                                        plot!(plot2, softvalues_hydro, name="MaxSoftCap")
                                    elseif sum(softvalues_hydro) < 0
                                        plot!(plot2, softvalues_hydro*-1, name="MinSoftCap
                                    end
                                end
                            end
                        end

                        push!(allplots,plot2)
                        @goto escape_label
                    end
                end

                # plants with unregulated and regulated inflow have one storage two waterba
                for flow in getbalanceflows(modelobjects)[prodbalance]
                    if !(flow in pumps) & !(flow in plants)
                        for arrow in getarrows(flow)
                            if isingoing(arrow) & (getbalance(arrow) == prodbalance)
                                for arrow1 in getarrows(flow)
                                    if !isingoing(arrow1)
                                        storagebalance = getbalance(arrow1)
                                        for storage in storages
                                            if getbalance(storage) == storagebalance

                                                # Plot identified reservoir
                                                l = findall(x -> x == storage, storages)
                                                @assert length(l) == 1
                                                plot2 = plot(sum(hydrolevels[:,:,l[1]],dim
                                                plot!(plot2, mean(sum(hydrolevels[:,:,l[1]

                                                # Plot reservoir restrictions
                                                if haskey(mainobjects,obj)
                                                    for trait in mainobjects[obj]
                                                        if trait isa BaseSoftBound
                                                            for j in 1:numperiods_hydro
                                                                softvalues_hydro[j] = getrh
                                                            end
                                                            if sum(softvalues_hydro) > 0
                                                                plot!(plot2, softvalues_hy
                                                            elseif sum(softvalues_hydro) <
                                                                plot!(plot2, softvalues_hy
                                                            end
                                                        end
                                                    end
                                                end

                                                push!(allplots,plot2)
                                                @goto escape_label
                                            end
                                        end
                                    end
                                end
                            end
                        end
```

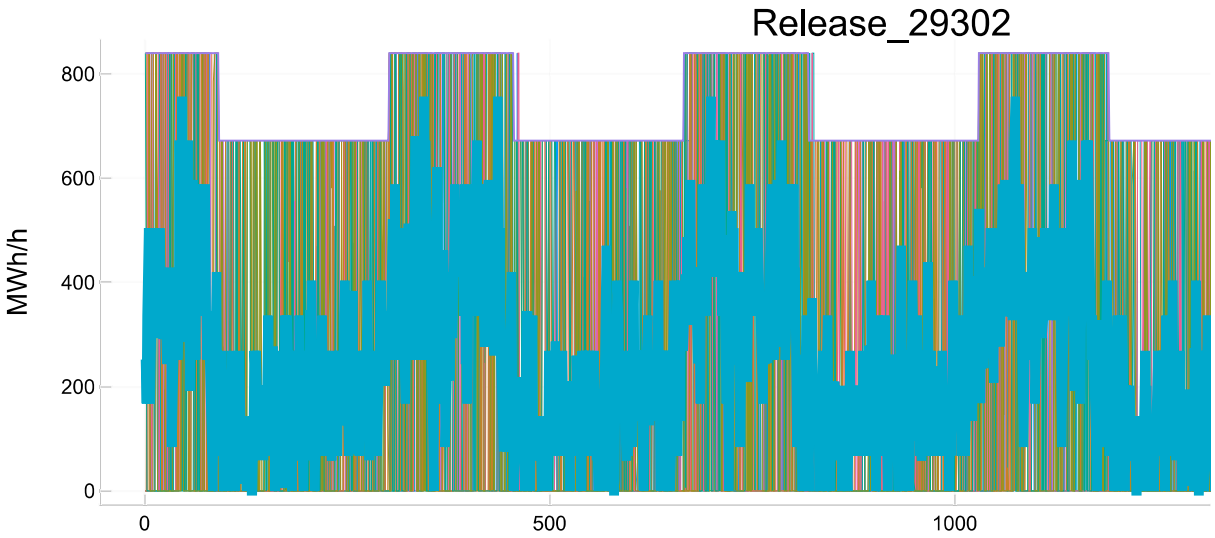
```
                    end
                end
            end
        end
    end
    @label escape_label

    # Bypasses and spills
    arrows = getarrows(plant)
    for arrow in arrows
        if !isingoing(arrow)
            prodbalance = getbalance(arrow) # first identify water balance over plant

            # bypass/spill from first water balance over plant
            for flow in getbalanceflows(modelobjects)[prodbalance]
                if !(flow in plants) & !(flow in pumps)
                    for arrow1 in getarrows(flow)
                        if !isingoing(arrow1) & (getbalance(arrow1) == prodbalance)

                            # Plot identified bypass/spill
                            l = findall(x -> x == flow, bypasspills)
                            @assert length(l) == 1
                            plot3 = plot(sum(bypasspill[:,:,l[1]],dims=3),label=scenye
                            plot!(plot3, mean(sum(bypasspill[:,:,l[1]],dims=3),dims=2)

                            # Plot bypass restrictions
                            if haskey(mainobjects,flow)
                                for trait in mainobjects[flow]
                                    if trait isa BaseSoftBound
                                        for j in 1:numperiods_hydro
                                            softvalues_hydro[j] = getrhsterm(prob, get
                                        end
                                        if sum(softvalues_hydro) > 0
                                            plot!(plot3, softvalues_hydro,name="MaxSof
                                        elseif sum(softvalues_hydro) < 0
                                            plot!(plot3, softvalues_hydro*-1,name="Min
                                        end
                                    end
                                end
                            end
                            push!(allplots,plot3)
                        end
                    end
                end
            end

            # if storage connected to waterbalance, don't search further up
            for storage in storages
                if getbalance(storage) == prodbalance
                    @goto escape_label1
                end
            end

            # bypass/spill from second water balance over plant (dependant on dataset)
            for flow in getbalanceflows(modelobjects)[prodbalance]
                if !(flow in pumps) & !(flow in plants)
                    for arrow in getarrows(flow)
                        if isingoing(arrow) & (getbalance(arrow) == prodbalance)
                            for arrow in getarrows(flow)
                                if !isingoing(arrow)
                                    storagebalance = getbalance(arrow)
                                    for storage in storages
                                        if getbalance(storage) == storagebalance # ide
                                            for flow1 in getbalanceflows(modelobjects)
                                                if !(flow1 == flow)
                                                    for arrow1 in getarrows(flow1)
                                                        if !isingoing(arrow1) & (getba

                                                            # Plot identified bypass/s
```

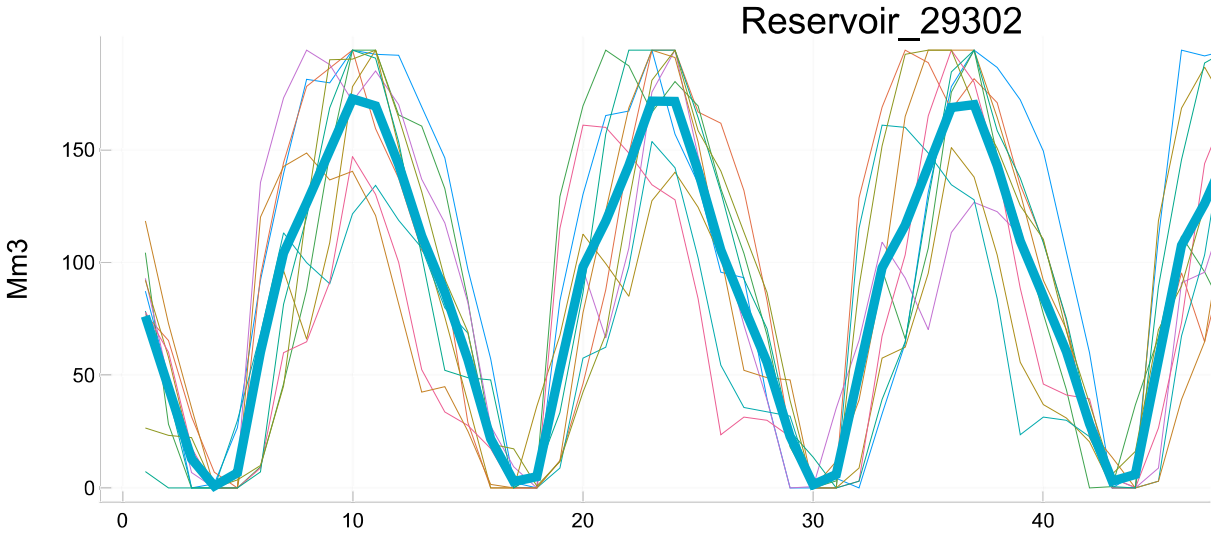
```
                                                                l = findall(x -> x == flow
                                                                @assert length(l) == 1
                                                                plot3 = plot(sum(bypasspil
                                                                plot!(plot3, mean(sum(bypa

                                                                # Plot bypass restrictions
                                                                if haskey(mainobjects,flow
                                                                    for trait in mainobjec
                                                                        if trait isa BaseS
                                                                            for j in 1:num
                                                                                softvalues
                                                                            end
                                                                            if sum(softvalu
                                                                                plot!(plot
                                                                            elseif sum(sof
                                                                                plot!(plot
                                                                            end
                                                                        end
                                                                    end
                                                                end
                                                                push!(allplots,plot3)
                                                            end
                                                        end
                                                    end
                                                end
                                            end
                                        end
                                    end
                                end
                            end
                        end
                    end
                end
            end
        end
        @label escape_label1
        display(plot(allplots...,layout=(length(allplots),1),size=(900,300*length(allplots
    end

    # Remaining pumps
    for i in 1:length(pumps)
        plot5 = plot(sum(consumption[:,:,i],dims=3),label=scenyears, title=getinstancename
        plot!(plot5, mean(sum(consumption[:,:,i],dims=3),dims=2),name="Mean", linewidth=5,
        display(plot5)
    end
end

runwatercourse()
```

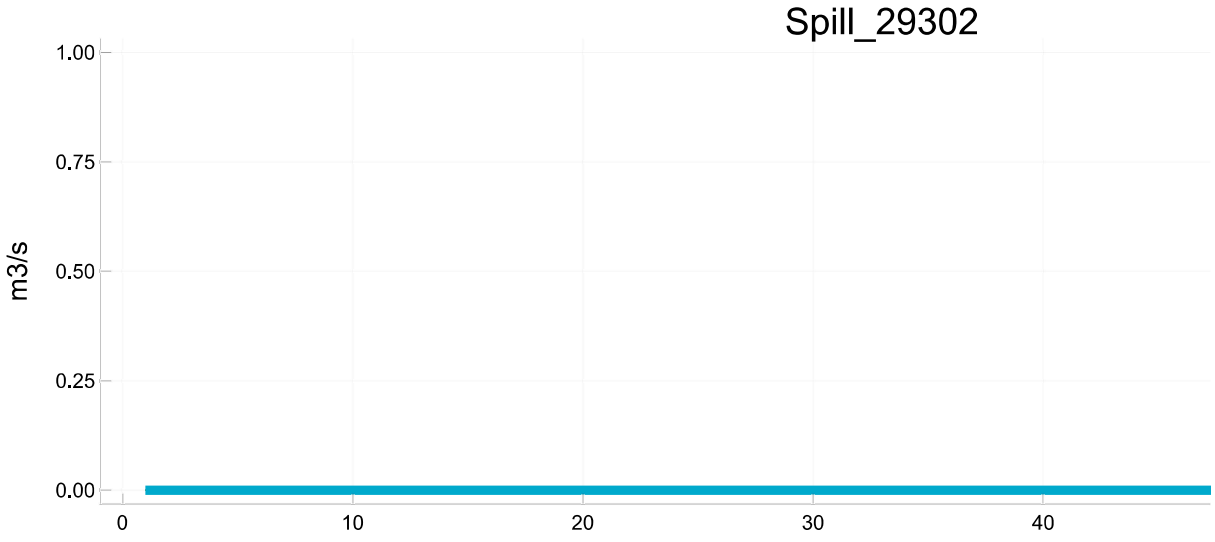
```
  2.188072 seconds (2.81 M allocations: 157.440 MiB, 1.69% gc time, 98.62% compilation tim
e)
  0.902614 seconds (1.04 M allocations: 47.811 MiB, 98.74% compilation time)
  0.136621 seconds
Objective value in scenario 1: -9.11965370312589e8
  0.009565 seconds (153.68 k allocations: 3.018 MiB)
  0.048091 seconds
Objective value in scenario 2: -9.094558706862497e8
  0.009651 seconds (153.68 k allocations: 3.018 MiB)
  0.051283 seconds
Objective value in scenario 3: -8.910715585750921e8
  0.010771 seconds (153.68 k allocations: 3.018 MiB)
  0.058800 seconds
Objective value in scenario 4: -8.253494755134512e8
  0.011319 seconds (153.68 k allocations: 3.018 MiB)
  0.064163 seconds
Objective value in scenario 5: -8.958860111253073e8
  0.011096 seconds (153.68 k allocations: 3.018 MiB)
  0.042462 seconds
Objective value in scenario 6: -9.681197454077709e8
  0.052493 seconds (153.68 k allocations: 3.018 MiB, 79.69% gc time)
  0.053895 seconds
Objective value in scenario 7: -9.663429050172322e8
  0.009617 seconds (153.68 k allocations: 3.018 MiB)
  0.050911 seconds
Objective value in scenario 8: -1.0299819329401647e9
  0.009650 seconds (153.68 k allocations: 3.018 MiB)
  0.050624 seconds
Objective value in scenario 9: -1.043410977307665e9
  0.009484 seconds (153.68 k allocations: 3.018 MiB)
  0.063147 seconds
Objective value in scenario 10: -9.966831637050351e8
```

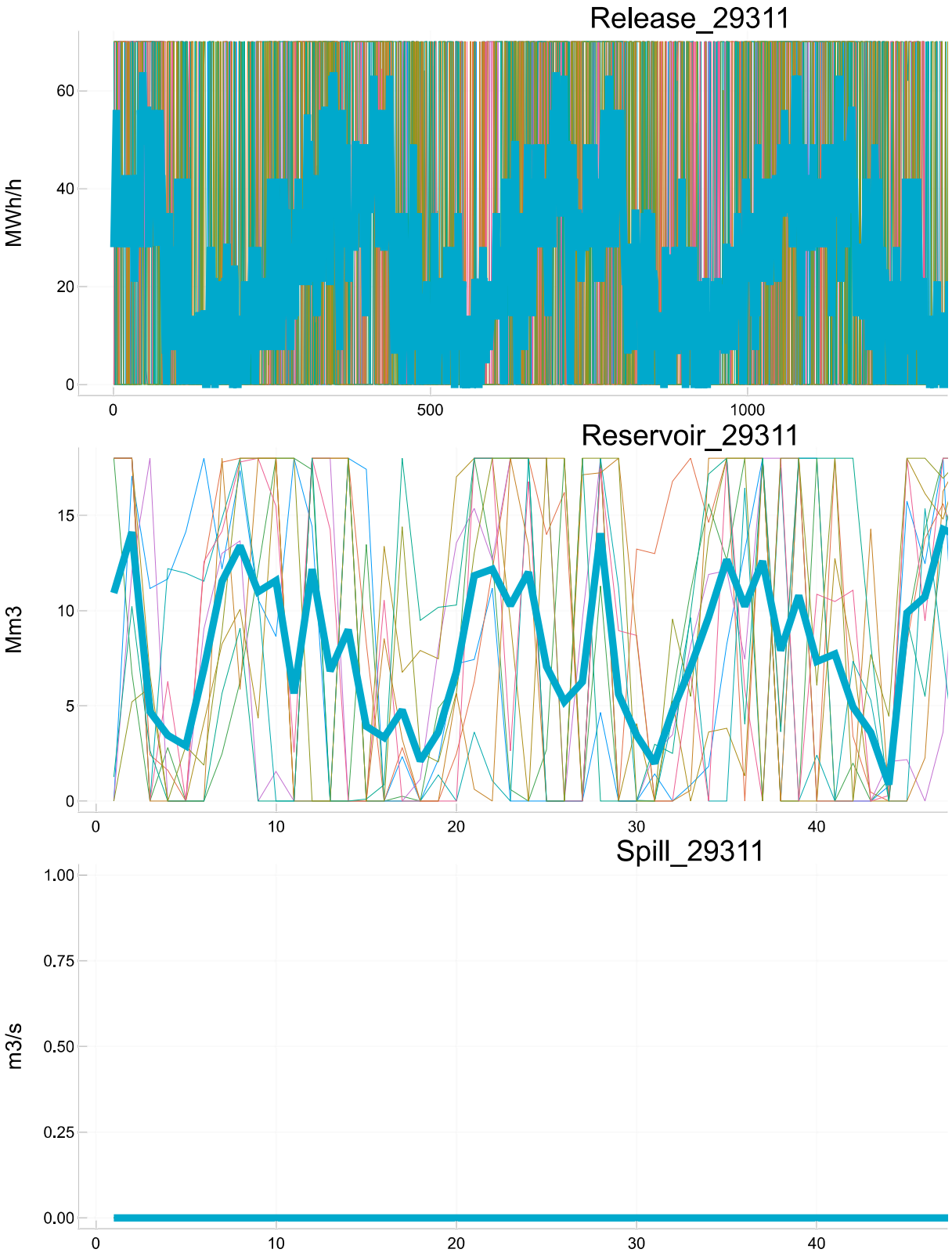
6×4 DataFrame

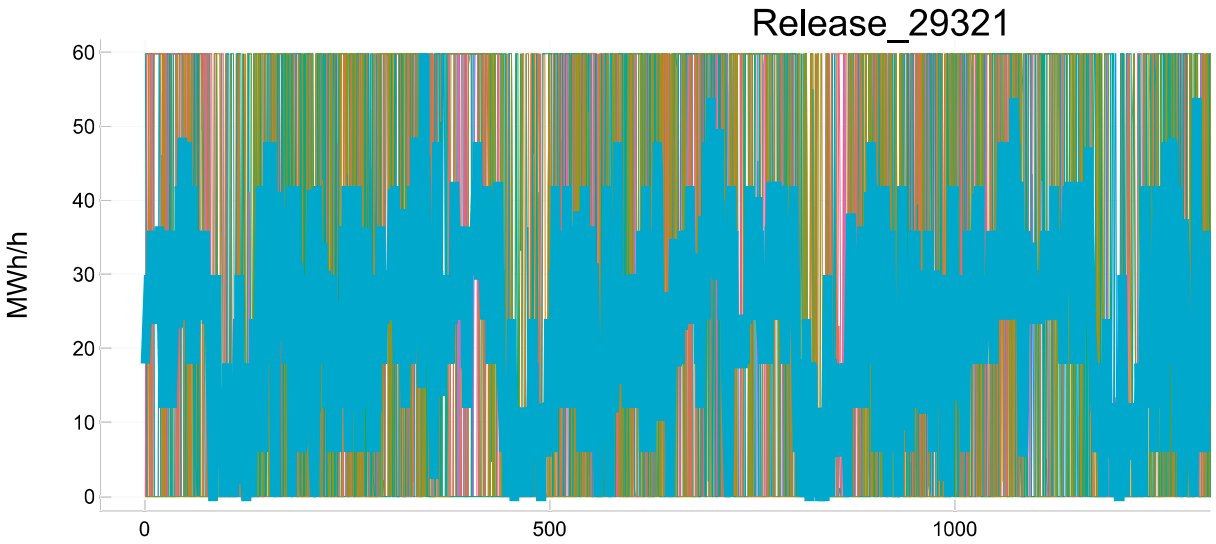
Row	Supplyname	Yearly_supply_GWh	Demandname	Yearly_demand_GWh
	String?	Float64?	String?	Float64?
1	Release_29302	2251.8	Pump_29326	480.763
2	Release_29326	545.907	missing	missing
3	Release_29311	221.023	missing	missing
4	Release_29321	203.34	missing	missing
5	Release_29301	137.985	missing	missing
6	Release_29303	25.1345	missing	missing

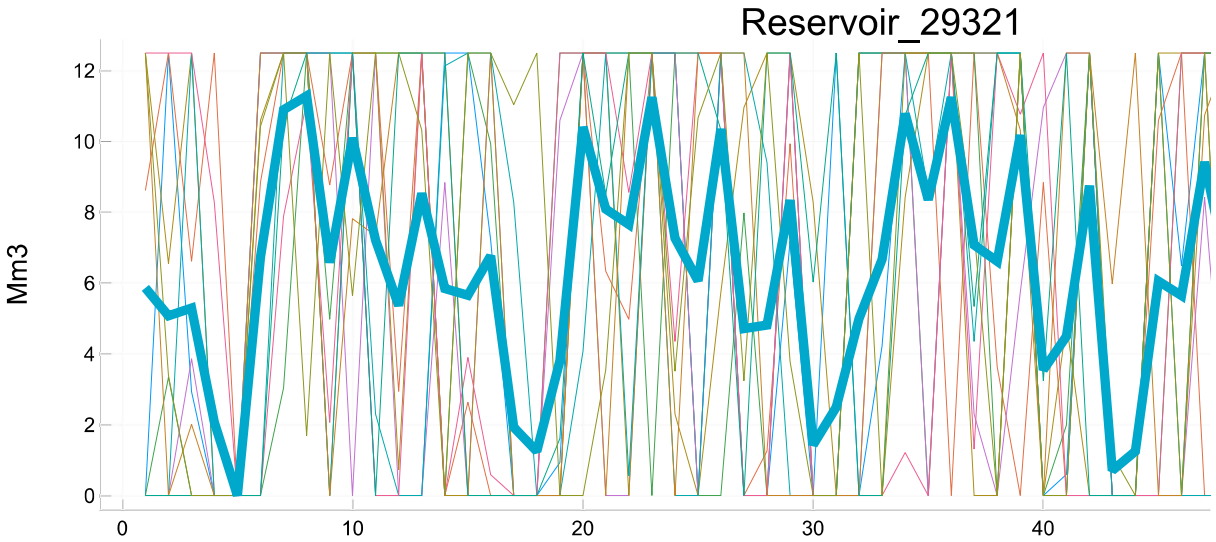

Release_29302
MWh/h
800
600
400
200
0
0
500
1000

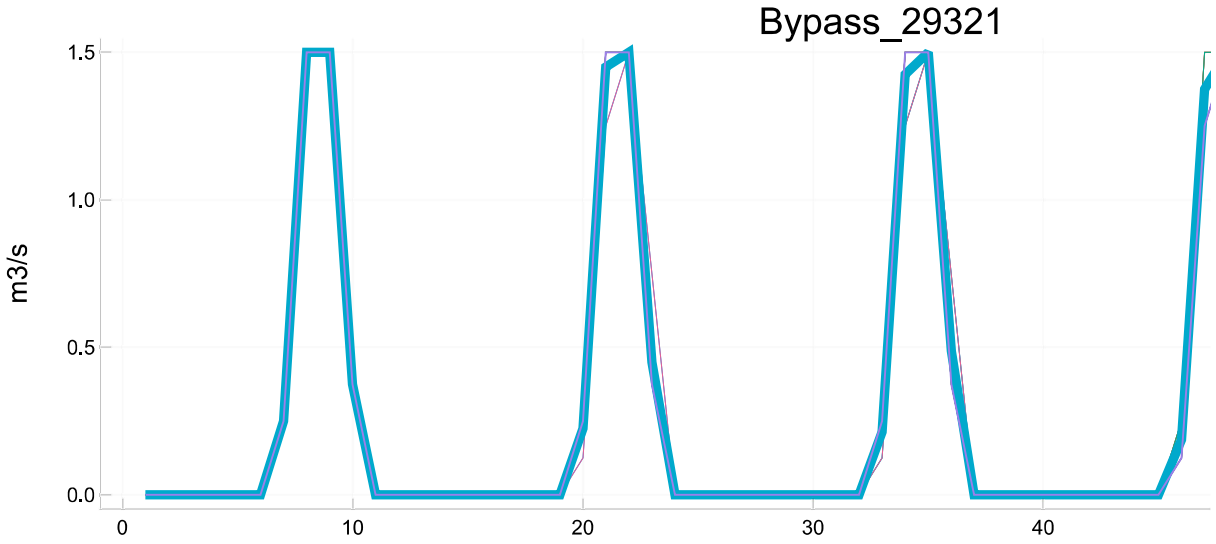

Reservoir_29302
Mm3
150
100
50
0
0
10
20
30
40


Spill_29302
m3/s
1.00
0.75
0.50
0.25
0.00
0
10
20
30
40

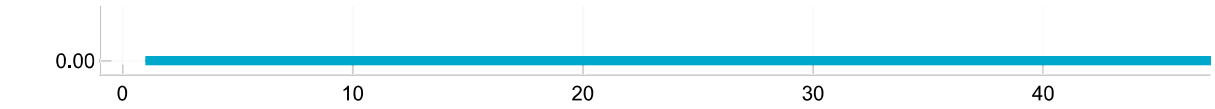

Release_29311
MWh/h
0
20
40
60
0
500
1000
Reservoir_29311
Mm3
0
5
10
15
0
10
20
30
40
Spill_29311
m3/s
0.00
0.25
0.50
0.75
1.00
0
10
20
30
40

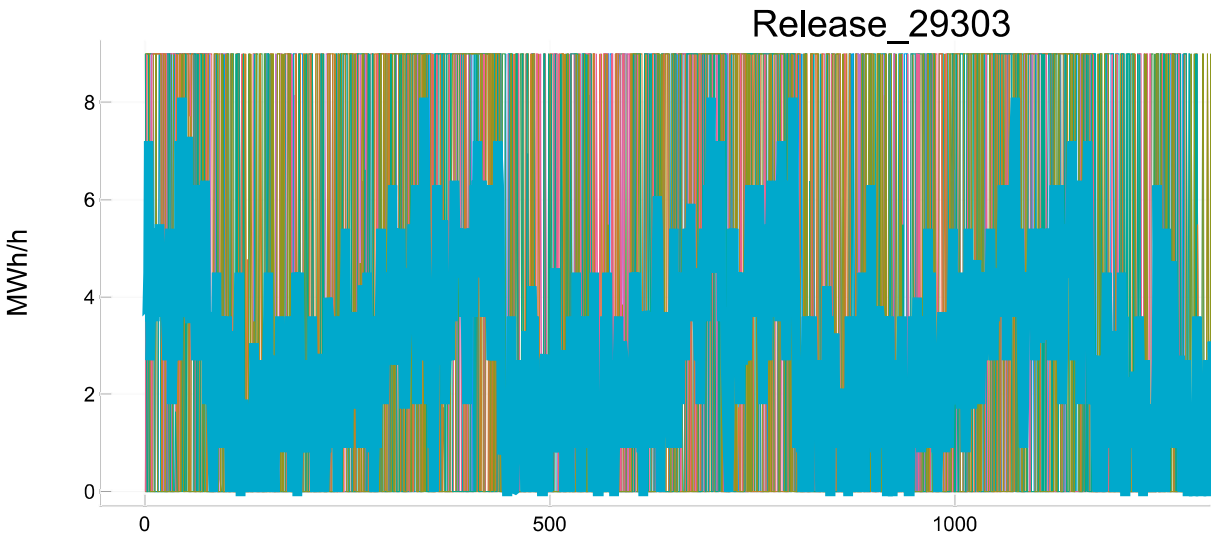

Release_29321
MWh/h
60
50
40
30
20
10
0
0
500
1000

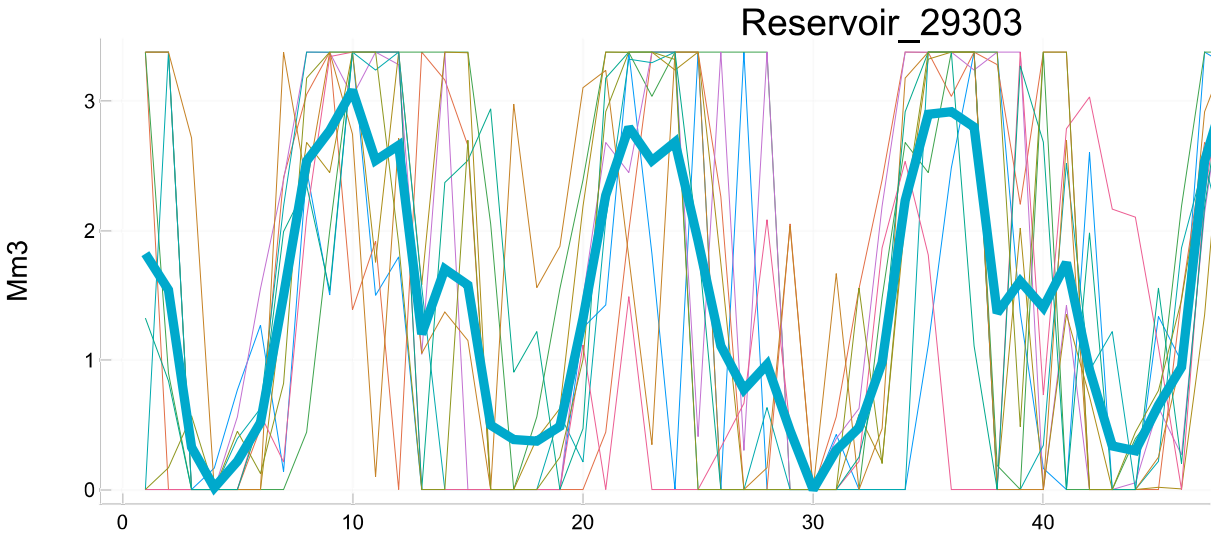

Reservoir_29321
Mm3
12
10
8
6
4
2
0
0
10
20
30
40

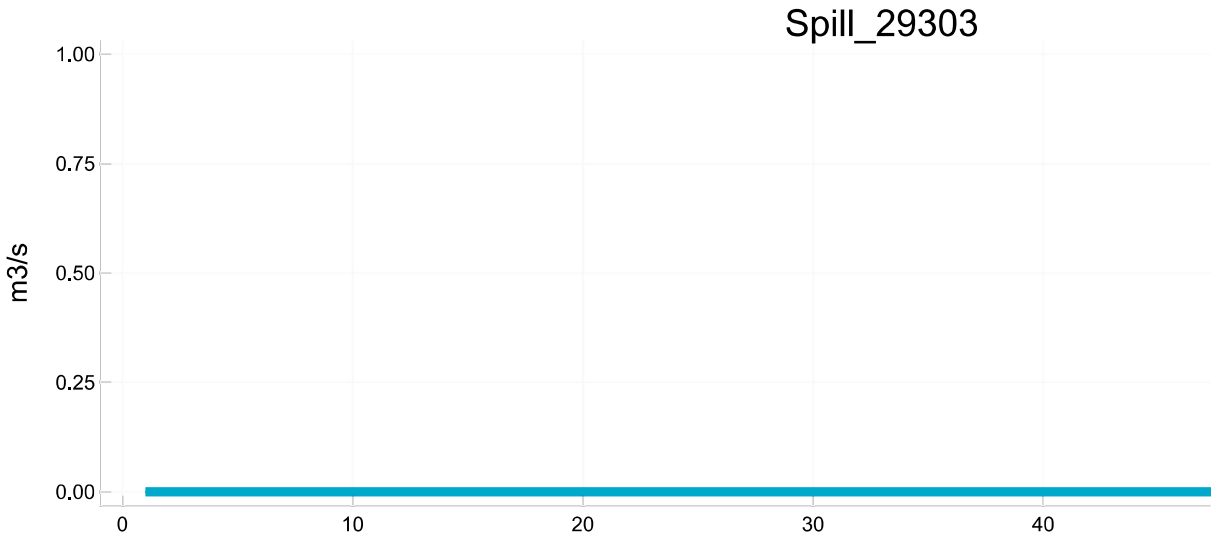

Bypass_29321
m3/s
1.5
1.0
0.5
0.0
0
10
20
30
40

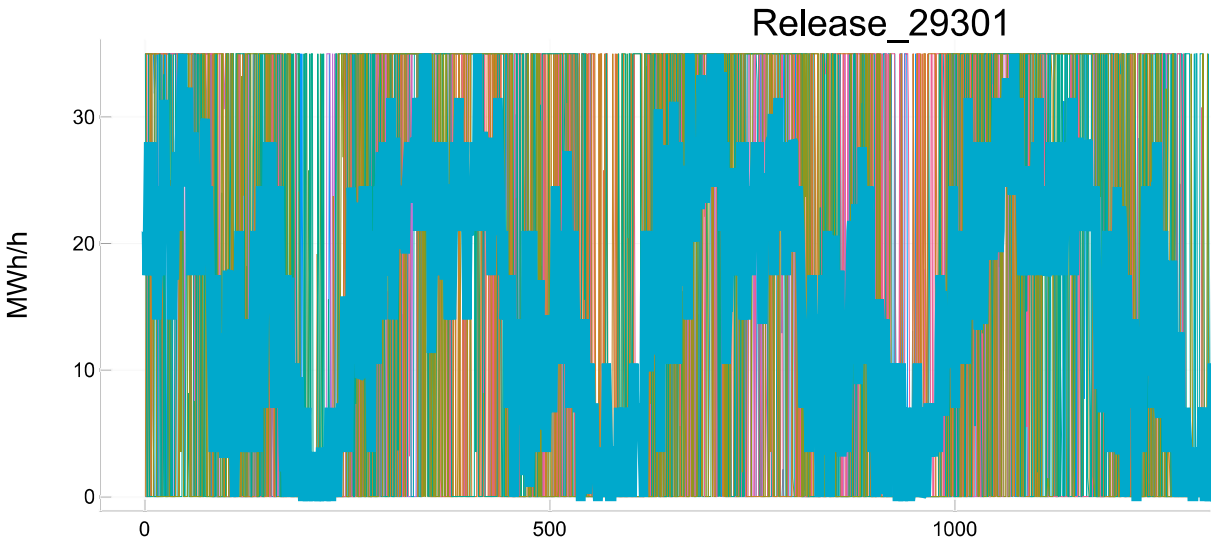

Spill_29321
m3/s
1.00
0.75
0.50
0.25

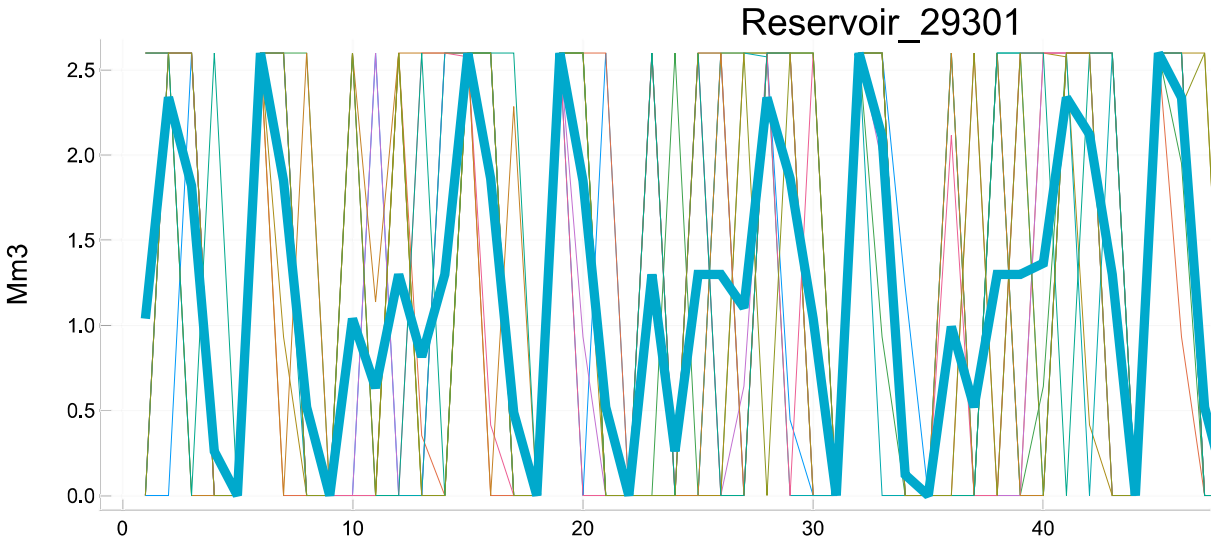

0.00
0
10
20
30
40

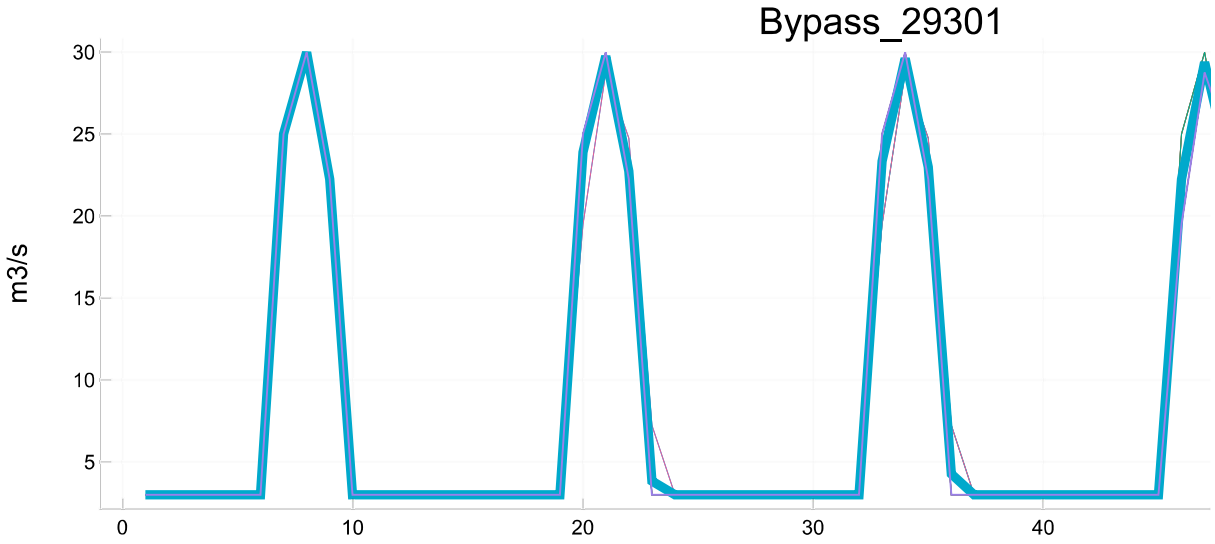

Release_29303
MWh/h
8
6
4
2
0
0
500
1000


Reservoir_29303
Mm3
3
2
1
0
0
10
20
30
40

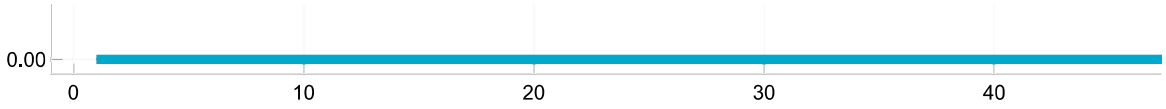

Spill_29303
m3/s
1.00
0.75
0.50
0.25
0.00
0
10
20
30
40

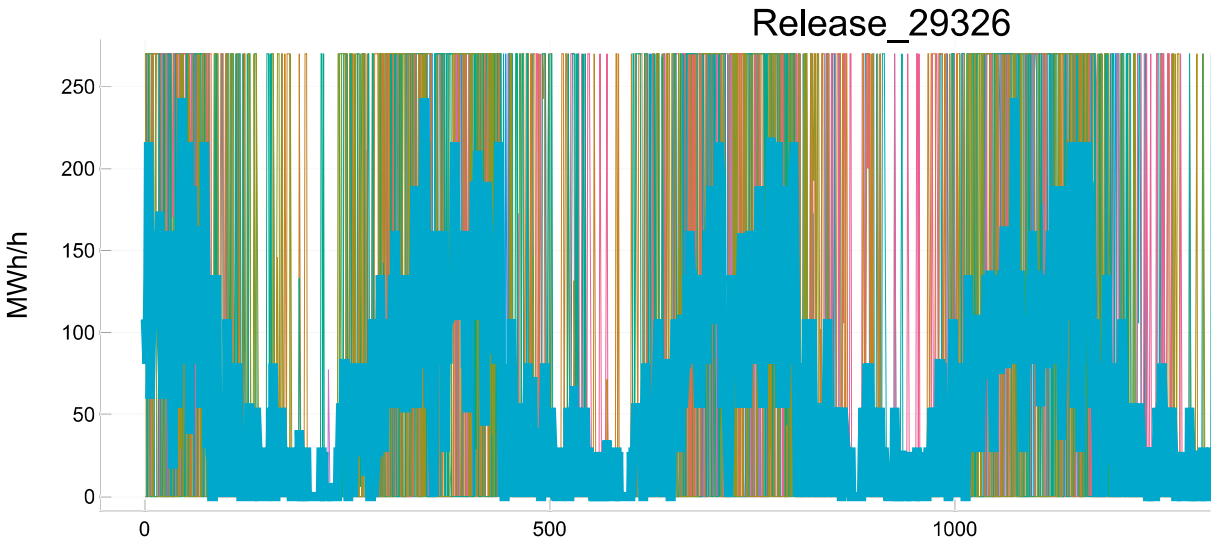

Release_29301
MWh/h
0
10
20
30
0
500
1000

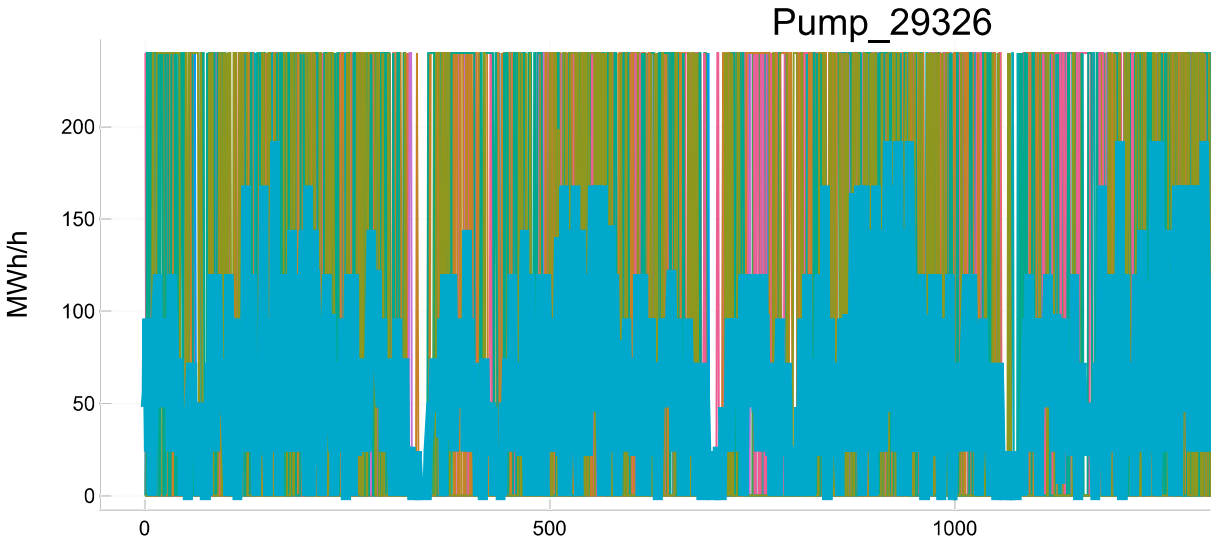

Reservoir_29301
Mm3
0.0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
40

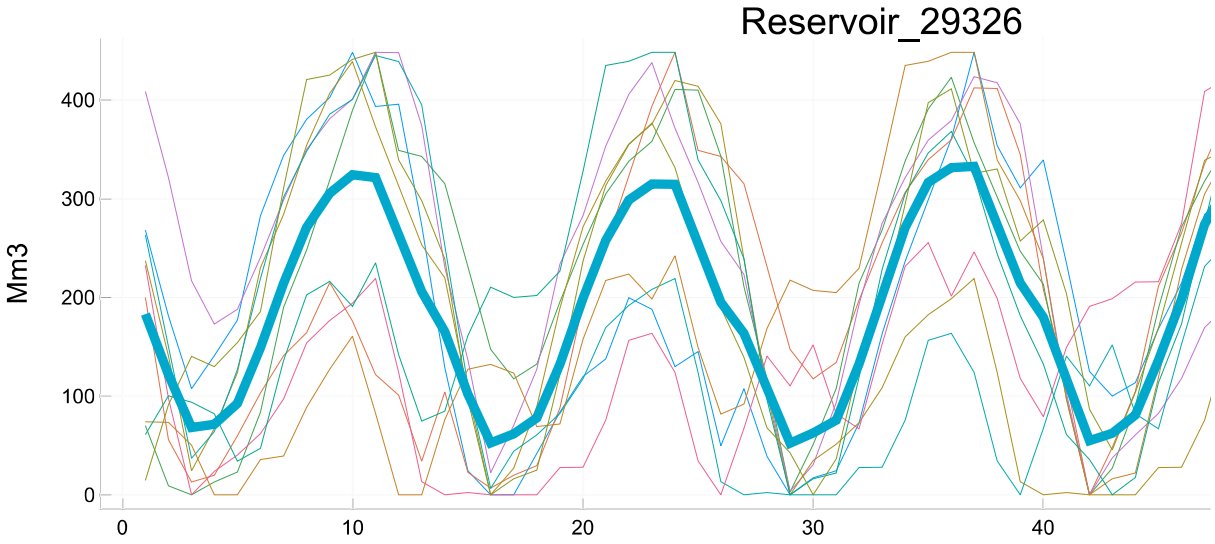

Bypass_29301
m3/s
5
10
15
20
25
30
0
10
20
30
40


Spill_29301
m3/s
0.25
0.50
0.75
1.00

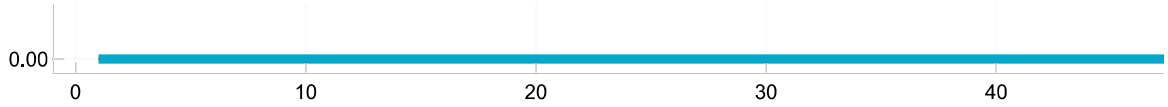

0.00
0
10
20
30
40


Release_29326
MWh/h
250
200
150
100
50
0
0
500
1000


Pump_29326
MWh/h
200
150
100
50
0
0
500
1000


Reservoir_29326
Mm3
400
300
200
100
0
0
10
20
30
40


Spill_29326
m3/s
1.00
0.75
0.50
0.25



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