# Intelligent distributed systems

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# Outline

# Outline

1. SCADA: A Case Study
   - What is a hydroelectric power plant?
   - The plant of Primiero Energia
   - SCADA
2. System Simulation

# SCADA

## Case Study

In these slides, we will present a practical application of a SCADA system for *hydroelectric power plants* deployed in the Trentino Province.
The facility belongs to *Primiero Energia*, which is a fundamental part of the energy production system of Primiero Valley.
The following slides have been inspired by the project developed by *Matteo Gaio*, a former student of the course of "*Distributed Systems for Automation and Robotics*".

# Outline

# Hydroelectricity

*Hydroelectricity* is the term referring to electricity generated by hydropower.

The production of electrical power is carried out through the use of the *gravitational force of falling or flowing water*.

In practice, the facility transforms *potential energy* into *kinetic energy* in order to rotate *hydro turbines*.

It is the most widely used form of *renewable energy*, accounting for 16% percent of global electricity generation.

The environmental impact generated by a hydropower facility is *one of the smallest*.

# Hydroelectricity

## The facility as a whole

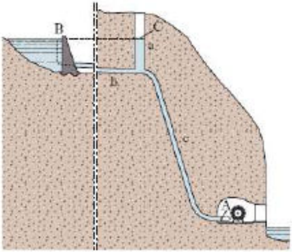


Figure: Hydroelectric facility scheme (courtesy of Google Images).

In the majority of the cases, the *catch basins* (B) are built up using *dams* of different dimensions.

The catch basin constitutes the *upper reservoir*.

# Hydroelectricity

## The facility as a whole

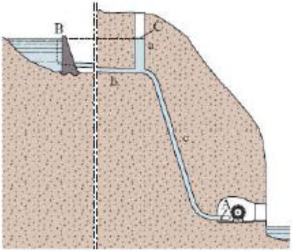



Figure: Hydroelectric facility scheme (courtesy of Google Images).

From the catch basin, the *penstock pipe* (b,c) departs, letting the water to flow towards the facility.

The characteristics of the pipe determine the *flow rate* and the overall *water jump* (head), hence the *power* involved.

# Hydroelectricity

## The facility as a whole

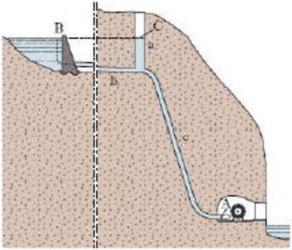


Figure: Hydroelectric facility scheme (courtesy of Google Images).

The power is necessary to design the *water turbine* (A) that generates the *hydroelectricity*.

# Hydroelectricity

## The facility as a whole

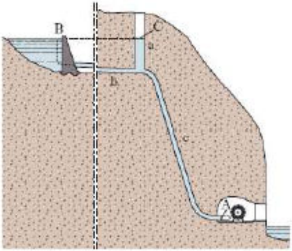



Figure: Hydroelectric facility scheme (courtesy of Google Images).

To avoid mechanical problems deriving from pressure jumps (e.g., when a duct is closed), an additional *discharge pipe* (C) is available.

# Hydroelectricity

## The facility as a whole

Figure: Hydroelectric facility penstock pipe (courtesy of Google Images).

After the turbine, the water carried by the penstock pipe is deployed in the *lower reservoir*, i.e., lower basin.
The penstock pipe is usually endowed with *pressure valves* that regulates the flow rate with a mechanical feedback.

# Hydroelectricity

## The Turbine choice

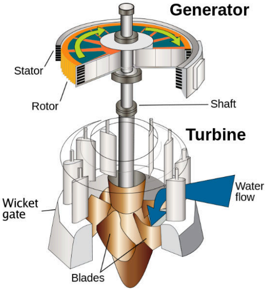



Figure: Hydraulic turbine and electrical generator, cutaway view (courtesy of U.S. Army Corps of Engineers).

The role of the turbine is to convert mechanical energy into *electric energy*, generated by the rotation of the *rotor*.

# Hydroelectricity

## The Turbine choice

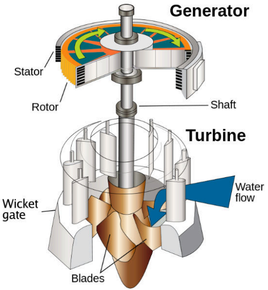



Figure: Hydraulic turbine and electrical generator, cutaway view (courtesy of U.S. Army Corps of Engineers).

The generated energy is then transformed into *high voltage* power for transmission. This way, the *transmission efficiency* is the highest, i.e., reduction of Joule effect.

# Hydroelectricity

## The Turbine choice

The power generated by the turbine is given by

$$W = \rho g \bar{h} Q \eta \text{ [W]}, \text{ where } \bar{h} = \Delta z - JL,$$

and depends on:

- The fluid density $\rho$ [kg/m$^3$];
- Gravitational acceleration $g \approx 9.8$ [m/s$^2$];
- The head $\Delta z$ [m];
- Mechanical pressure leaks $JL$ [m], reducing the potential energy of the upper reservoir;
- Flow rate $Q$ [m$^3$/s];
- Mechanical efficiency $\eta$.

# Hydroelectricity

## The Turbine choice

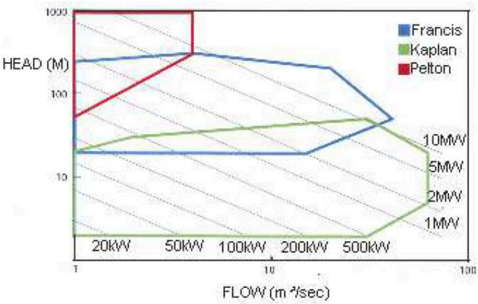



Figure: Turbine efficiency for three cases: Pelton, Francis and Kaplan (courtesy of Google Images).

Depending on the characteristic of the plant and on the desired energy production, different choices are available.

# Hydroelectricity

## The Turbine choice

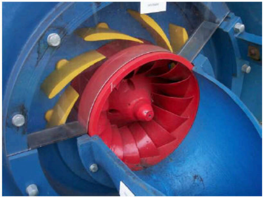
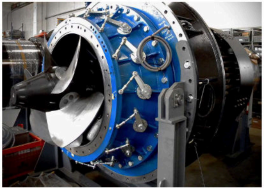
a)  b)  c) 

Figure: Pelton turbine (a), Francis turbine (b) and Kaplan turbine (c) (courtesy of Google Images).

# Hydroelectricity

## The Turbine choice

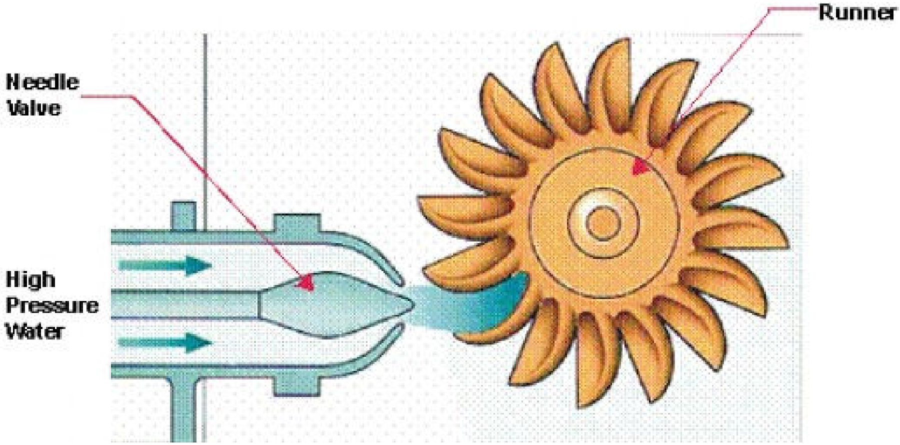



Figure: The pressure generated in the Pelton turbine (courtesy of Google Images).

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# Primiero Energia

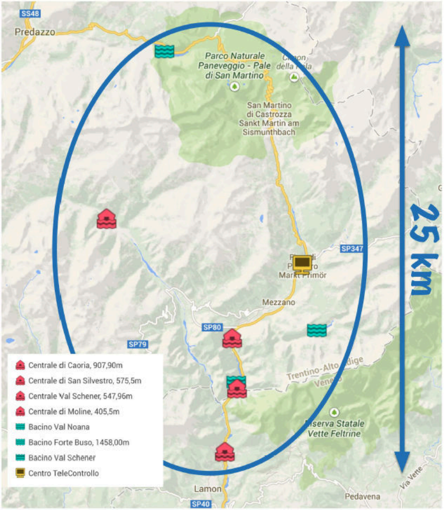
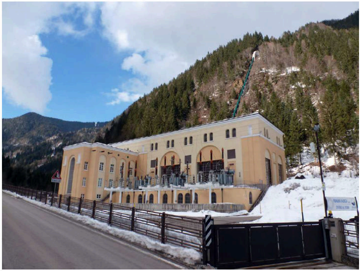



Figure: Production sites of Primiero Energia.

# Primiero Energia



Facility of *Caoria*:

- **Catch basin**: Forte Buso lake [1395, 1458] meters s.l.;
- **Basin capacity**: 28.000.000 [$m^3$];
- **Flow rate**: 9 [$m^3/s$];
- **Power**: 38.1 [MW];
- **Maximum Electric Power**: 42 [MVA]
- **Output voltage**: 9 [kV].

# Primiero Energia

Facility of *San Silvestro*:

- **Catch basin**: Artificial lake [795, 881] meters s.l.;
- **Flow rate**: 8 [$\mathrm{m}^3$/s];
- **Power**: 25.5 [MW];
- **Maximum Electric Power**: 30 [MVA]
- **Output voltage**: 9 [kV].

# Primiero Energia


Facility of *Val Schener*:

- **Catch basin**: Val Schener lake [552, 565] meters s.l.;
- **Basin capacity**: 4.800.000 [$m^3$];
- **Flow rate**: 16 [$m^3/s$];
- **Power**: 2.7 [MW];
- **Maximum Electric Power**: 3.25 [MVA];
- **Output voltage**: 5 [kV].

# Primiero Energia

Facility of *Moline*:

- **Catch basin**: Val Schener lake [552, 566] meters s.l.;
- **Basin capacity**: 4.800.000 [$m^3$];
- **Flow rate**: 16 [$m^3/s$];
- **Power**: 24.75 [MW];
- **Maximum Electric Power**: 30 [MVA]
- **Output voltage**: 9 [kV].

# Outline

# SCADA of Primiero Energia

Since the plant is operating from the '30s, the automation systems have been *gradually integrated*.

The system, as already presented, is subdivided into four levels:

- Field automation (Level I);
- Field communication (Level II);
- SCADA central host (Level III);
- SCADA Enterprise (Level IV).

# SCADA of Primiero Energia

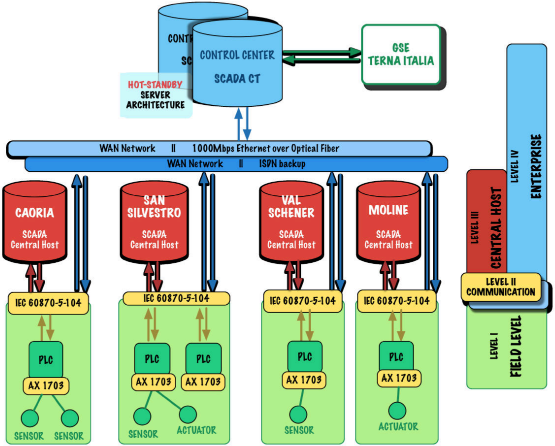



Figure: SCADA structure.

# SCADA of Primiero Energia

## Level I - Field automation

The SCADA comprises a set of PLCs on the field conceived for:

- *Automation*: local control of pressure valves;
- *Measurements*: measurement collection of local electrical and mechanical quantities.

By means of PLCs, the human operator in the central station can *monitor* all the quantities of interest and, in case, *control* the behaviour of the local system.

# SCADA of Primiero Energia

## Level II - Field communication

For the communication part, the system relies on a proprietary fieldbus named *Ax-1703*, which is a serial bus at 16 Mbps developed by *Andritz*. The reason of this choice is that Andritz provide the *overall SCADA system*.

# SCADA of Primiero Energia

## Level III - Central Host

At this level, the SCADA system monitors *with detailed information* the production facility, offering the possibility to modify its behaviour *autonomously or manually*.

# SCADA of Primiero Energia

## Level III - Central Host

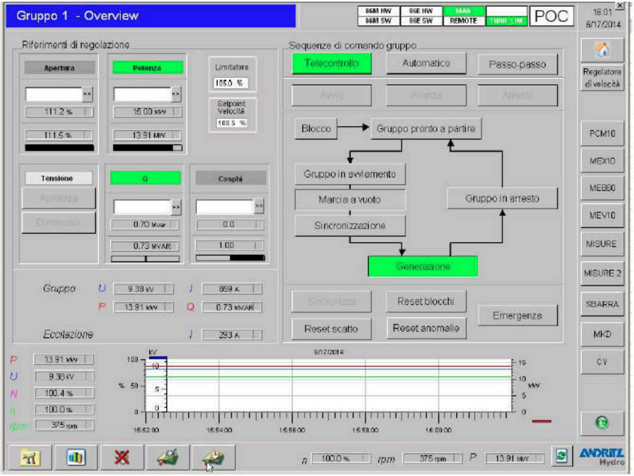



Figure: HMI of Level III related to an energy production sub-system (courtesy of

# SCADA of Primiero Energia

## Level IV - Enterprise

Due to the geographical distribution of the system at hand, at the Enterprise level the SCADA system provides *information on the overall production plant*.
This point is crucial since the energy production is mediated with the *main energy provider*, Terna Energia in this case.
At this level, the *production plan* is detailed and, in case, modified on-line.

# SCADA of Primiero Energia

## Level IV - Enterprise

The monitored information at this level are:

- Measures, states, alarms and controls for *any production site* to verify the accordance with the production plan;
- Measures, states and alarms of the *catch basins*;
- Measures, states, alarms and controls for the *electric energy transformation station* for high voltage transmission.

The retrieved information *does not have to be too detailed*.

# SCADA of Primiero Energia

## Level IV - Enterprise

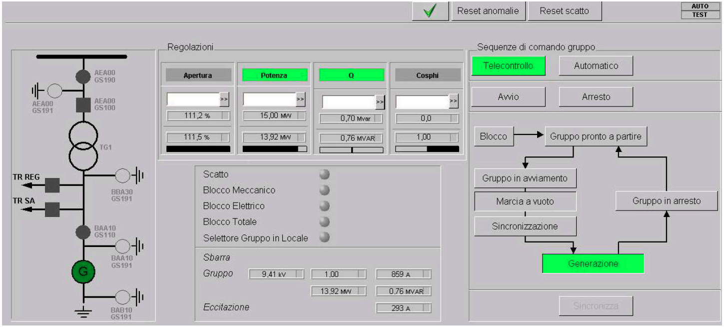



Figure: HMI of Level IV related to the overall system (courtesy of Primiero Energia).

# SCADA of Primiero Energia

## Level IV - Enterprise

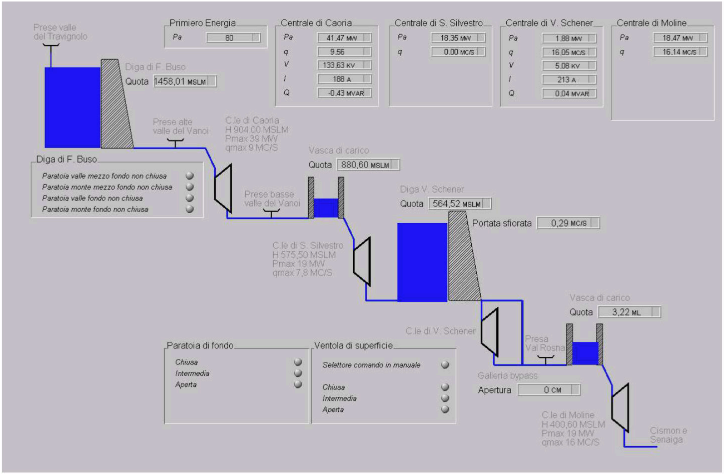



Figure: HMI of Level IV related to the catch basins (courtesy of Primiero Energia).

# SCADA of Primiero Energia

## Level IV - Enterprise

The communication infrastructure at the Enterprise level relies on *fiber optics*.
This is indeed an overkill, since the number of monitored variables is approximately 5000, that *generate a mean traffic of 30 KBs*.
Nonetheless, this choice guarantees a deterministic communication and the presence of a *back-up system based on ISDN*.

### Definition

*Integrated Services for Digital Network* (ISDN) is a set of communication standards for simultaneous digital transmission of voice, video, data, and other network services over the traditional circuits of the public switched telephone network.

# SCADA of Primiero Energia

## Level IV - Enterprise

The standards adopted for the automation and communication systems of the facility are:

- *IEC 61850* is a standard for the *electric substation*, and builds upon *TCP/IP over Fast Ethernet*, i.e., Ethernet on 100 Mbit/s, since the original Ethernet was on 10 Mbit/s;
- *IEC 60870-5* is a standard for the *remote control of geographically distributed energy production sites*, which is based on *Ethernet TCP/IP*.

# SCADA of Primiero Energia

## Redundancy

As we already pointed out, a SCADA system should provide *redundancy* for robustness to components failure.
The facility at hand foresees:

- *Parallelism between the central hosts and the enterprise level*. This is ensured by the field devices that can manage communications with both the systems;
- *Redundancy of the communication medium* using ISDN in parallel with the fiber optic. In case of a failure of the fiber optic, the failure will be notified in order to issue a prompt repairing activity;
- *Hot-standby of the server at the enterprise level*, using a mirroring server.

# SCADA of Primiero Energia

## Alarms

The *alarms* are forwarded to the central host and also to the server at the enterprise level.

Conditions of *pre-alarm* are also provided to the operators in order to prevent critical situations.

In case of an alarm, the operator will check the critical situation *against the historical data* in order to determine the proper actions to take.

The *restoring actions* are saved and stored to enrich the database of historical data.

# SCADA of Primiero Energia

## Software

Form a software view-point, the entire system is *Windows and Unix compatible*.

For communication, the software integrates the main drivers adopted for the specific system: IEC 60870-5-101, IEC 60870-5-104, IEC 61850, Object Linking and Embedding for Process Control (OPC) Foundation Server/Client, Modbus and *Profibus*.

# Outline

# System Simulation

The simulations we will carry out refers to a *simplified model* of the plant, which is accurate enough to highlight the features of a SCADA system. In particular, we will simulate a system with *three production sites*, endowed with: 1 *catch basin*, 1 *hydraulic turbine* and 1 *SCADA central host*. Moreover, the *central Enterprise level system* will be also considered. The role of this server is to: *supervise and assign* the requested power from the different sites; *monitor* the generated power, the basins' level and the presence of alarms.

# System Simulation

## Turbine Model

The model of the turbine adopted has been derived from R. A. Naghizadeh, S. Jazebi, B. Vahidi, "*Modeling Hydro Power Plants and Tuning Hydro Governors as an Educational Guideline*", International Review on Modelling and Simulations (I.RE.MO.S.), Vol. 5, N. 4, 2012.
It is based on a linearised version of a nonlinear model, that is in the Laplace domain

$$\frac{\Delta P_m}{\Delta Q} = 2\frac{b - t_w a s}{2b + t_w a s},$$

where $P_m$ is the *normalised turbine mechanical power*, while $Q$ is the *normalised rate flow*.
"Normalised" quantities are assumed to belong to $[0, 1]$.

# System Simulation

## Turbine Model

In the considered model

$$\frac{\Delta P_m}{\Delta Q} = 2\frac{b - t_w a s}{2b + t_w a s},$$

we assume that the *water starting-time* is

$$t_w = \frac{L\frac{Q_r}{\pi\frac{D}{2}^2}}{gH_r},$$

where $L$ is the length of penstock pipe [m], $g$ is the gravitational acceleration [m/s$^2$], $Q_r$ is the discharge rate [m$^3$/s], $D$ is the diameter of the penstock pipe [m] and $H_r$ is the net head (jump) [m].

# System Simulation

## Turbine Model

In the considered model

$$\frac{\Delta P_m}{\Delta Q} = 2\frac{b - t_w a s}{2b + t_w a s},$$

the values of $a$ and $b$, that correspond to the Taylor approximation of the hyperbolic tangent, are given by

$$a = 1 + \frac{5}{4}s^2\left(\frac{t_e}{\pi}\right)^2 + \frac{1}{4}s^4\left(\frac{t_e}{\pi}\right)^4$$

$$b = 1 + \frac{40}{9}s^2\left(\frac{t_e}{\pi}\right)^2 + \frac{16}{9}s^4\left(\frac{t_e}{\pi}\right)^4$$

being $t_e$ the *elastic time of penstock pipe* [s] that is given by

$$t_e = \frac{\text{penstock length}}{\text{pressure wave velocity in steel pipes}} = \frac{L}{pw},$$

with $pw = 1220$ [m/s] or $pw = 1440$ [m/s] for steel pipes or cement tunnels, respectively.

# System Simulation

## Catch basin model

The simplified model of the *water volume* $L(t)$ in the catch basin is given by

$$\dot{L}(t) = A(t) - \left[Q(t) + O_d(t) + D_m(t)\right],$$

where $A(t)$ is the rate natural input, $Q(t)$ is the rate of flow in the penstock pipe, $O_d(t)$ is the over discharge and $D_m(t)$ is the minimum constant water discharge to reduce the environmental impact and sustain preexistent rivers, valleys, etc. All the quantities are measured in [m$^3$/s].

# System Simulation

## Central Host Work

The work carried out by the central host in the simulation is:

- *Maintain the level of the catch basin between the maximum and minimum level* and, in case, generate alarms if the limits are exceeded. If the level is greater than the maximum, the natural discharge is activated; if the level goes below the minimum level, no power is produced;
- *Regulate the water flow rate* in the penstock pipe in order to meet the desired level of generated power. The water flow rate can be regulated using a simple PI controller.

# System Simulation

## Enterprise Work

The work carried out at the Enterprise level in the simulation is:

- *Measure the power production for every substation* as a normalised number function of the catch basin level $L(t)$, i.e., $\leq 0$, no power production possible, $(0, 1]$ power production available, $> 1$ basin water exceeded;
- *Compute the power request for each production site* according to the power availability, as computed at the previous step;
- *Generate alarms* according to the situations depicted at the first point or whenever the requested power production cannot be met.

# System Simulation

Caoria: parameters adopted

Pr $=$ 38.1 [MW] $\rightarrow$ Rated generated power
Qr $=$ 9; [m$^3$/s] $\rightarrow$ Rated water flow
Od $=$ 380; [m$^3$/s] $\rightarrow$ Over discharge
Dm $=$ 25; [m$^3$/s] $\rightarrow$ Minimum constant water flow
A $=$ 30; [m$^3$/s] $\rightarrow$ Travignolo river
MinLevel $=$ 1395; [m] $\rightarrow$ Catch basin minimum allowable
MaxLevel $=$ 1458; [m] $\rightarrow$ Catch basin maximum allowable
Volume $=$ 28.000.000; [m$^3$] $\rightarrow$ Catch basin maximum volume
L $=$ 930; [m] $\rightarrow$ Penstock pipe length
D $=$ 1.5; [m] $\rightarrow$ Mean diameter
Hr $=$ 551; [m] $\rightarrow$ Rated head (water jump)

# System Simulation

San Silvestro: parameters adopted

Pr $= 25.5$; [MW] $\rightarrow$ Rated generated power
Qr $= 8$; [$m^3/s$] $\rightarrow$ Rated water flow
Od $= 220$; [$m^3/s$] $\rightarrow$ Over discharge
Dm $= 17$; [$m^3/s$] $\rightarrow$ Minimum constant water flow
A $= 20$; [$m^3/s$] $\rightarrow$ minor rivers
MinLevel $= 795$; [m] $\rightarrow$ Catch basin minimum allowable
MaxLevel $= 881$; [m] $\rightarrow$ Catch basin maximum allowable
Volume $= 10.000.000$; [$m^3$] $\rightarrow$ Catch basin maximum volume
L $= 525$; [m] $\rightarrow$ Penstock pipe length
D $= 2.25$; [m] $\rightarrow$ Mean diameter
Hr $= 306$; [m] $\rightarrow$ Rated head (water jump)

# System Simulation

## Moline: parameters adopted

Pr = 24.75; [MW] $\rightarrow$ Rated generated power
Qr = 16; [$m^3/s$] $\rightarrow$ Rated water flow
Od = 620; [$m^3/s$] $\rightarrow$ Over discharge
Dm = 20; [$m^3/s$] $\rightarrow$ Minimum constant water flow
A = 35; [$m^3/s$] $\rightarrow$ Cismon river
MinLevel = 552; [m] $\rightarrow$ Catch basin minimum allowable
MaxLevel = 565; [m] $\rightarrow$ Catch basin maximum allowable
Volume = 4.800.000; [$m^3$] $\rightarrow$ Catch basin maximum volume
L = 365; [m] $\rightarrow$ Penstock pipe length
D = 2.3; [m] $\rightarrow$ Mean diameter
Hr = 142.3; [m] $\rightarrow$ Rated head (water jump)