

Supplementary Material – Part 2 (S2):

Model for identifying the impacts of climate change on the operation of hydropower plants

SUMMARY

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S2-1. Model for identifying the impacts of climate change on the operation of hydropower plants

The model for identifying key indicators and areas of performance impacted by climate change in hydroelectric plants is based on a successful case of nature adaptation: ant colonies.

Biomimetics and bioinspiration were employed in the development of the model.

The forced-choice method between two alternatives (2AFC), commonly used to study the decision-making behaviour of animals, forms the basis of the developed model.

The developed model was implemented in a calculation spreadsheet, called Plan-2AFC, with its use summarised as inputting KPI performance, interpreting, and analysing the results.

The input data (Figure S2.1a, S2.1b, ..., S2.1i) and the parameters of the general equation for the input data (Figure S2.2a, S2.2b, ..., S2.2h) are presented below.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Finance, j = 1	Percentage of expenditure on operation and maintenance (O&M) activities (i=1) $y_{i,j} = y_{1,1}$	Expenditure on O&M activities versus O&M budget, expressed as a percentage (Ref.1).	The higher the intensity and duration of climate instability, the greater the financial expenditure on O&M, potentially exceeding the forecasted resources.
Finance, j = 1	Percentage of capital expenditure cost (i=2) $y_{i,j} = y_{2,1}$	Capital expenditure cost versus capital budget, expressed as a percentage (Ref.1).	The higher the intensity and duration of climate instability, the greater the financial expenditure on capital costs (acquisition of capital goods), potentially exceeding the forecasted resources.
Finance, j = 1	Percentage of special maintenance cost (i=3) $y_{i,j} = y_{3,1}$	Special maintenance cost versus special maintenance budget, expressed as a percentage (Ref.1). These refer to expenses associated with repairs, replacements, and upgrades that go beyond regular preventive and corrective maintenance activities.	The higher the intensity and duration of climate instability, the greater the financial expenditure on special maintenance (unplanned), potentially exceeding the forecasted resources.
Plant, j = 2	Plant availability factor (i=1) $y_{i,j} = y_{1,2}$	Relates the actual operation of the facility or equipment to the full capacity operation of the facility or equipment. This is a measure of actual operation compared to total operational capacity (Ref.2).	The higher the intensity and duration of climate instability, the lower the plant availability factor. Climate instability, for example, can cause structural insecurity, temporarily disabling the plant..
Plant, j = 2	Generation availability factor (i=2) $y_{i,j} = y_{2,2}$	Represents whether the generation availability value is above the level determined by the regulatory agency. Values above 1 indicate availability greater than required; values below 1 indicate availability less than required. The upper limit should be capped at a value of 1 (Ref.3).	The higher the intensity and duration of climate instability, the lower the generation availability factor. Climate instability can, for example, reduce the water levels in the reservoir, hindering generation.
Plant, j = 2	Planned shutdowns versus actual maintenance shutdowns (i=3) $y_{i,j} = y_{3,2}$	Number of planned shutdowns versus number of actual maintenance shutdowns (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of maintenance shutdowns. For instance, operating the turbine outside its design conditions reduces the lifespan of equipment and requires intensified O&M activities.
Plant, j = 2	Forced shutdown rate per unit (i=4) $y_{i,j} = y_{4,2}$	Percentage of emergency maintenance (Ref.2).	The higher the intensity and duration of climate instability, the greater the number of forced shutdowns. For example, operating the turbine outside its design conditions may force equipment to stop and require emergency O&M activities..
Plant, j = 2	Spilled water discharge (i=5) $y_{i,j} = y_{5,2}$	Percentage of the plant's average inflow (Ref.1).	The higher the intensity and duration of climate instability, the lower the volume of water spilled. For instance, during a severe drought condition, to maintain the minimum operational level, the minimum amount of water will be spilled.

Ref.1-Ref.3 adapted from [1], [2], [3], respectively.

Figure S2.1a. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Plant, j = 2	Achieved generation versus theoretical production (i=6) $y_{i,j} = y_{6,2}$	Measures the relationship between the amount of energy produced and the production capacity during a given period (Ref.1).	The higher the intensity and duration of climate instability, the lower the achieved generation will be. For example, during a severe drought condition, water levels in the reservoir will be reduced, leading to a decrease in energy generation.
Environmental Impact, j = 3	Non-compliance with environmental flow, ecological flow (i=1) $y_{i,j} = y_{1,3}$	Number of instances of non-compliance with environmental flow obligations per week (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of non-compliance events related to ecological flow. For example, in the case of a severe drought, the need for minimum generation may impact the ecological flow, leading to non-compliance.
Environmental Impact, j = 3	Pollutant discharge (i=2) $y_{i,j} = y_{2,3}$	Number of releases of environmentally harmful products, such as oil, sf6 (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of pollutant discharge events. For example, in a severe drought condition, intensified maintenance activities in workshops may exceed the capacity of oil and grease separators, resulting in pollutant discharge events.
Environmental Impact, j = 3	Non-compliance with dam safety regulations (i=3) $y_{i,j} = y_{3,3}$	Number of violations of dam safety standards (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of non-compliance events regarding dam safety. For instance, during prolonged rainfall, longitudinal and transverse cracks in dams may intensify..
Environmental Impact, j = 3	Non-compliance with water and sewage treatment regulations (i=4) $y_{i,j} = y_{4,3}$	Number of occurrences of non-compliance in domestic water and sewage treatment (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of non-compliance events in water and sewage treatment. For example, during prolonged drought conditions, water quality may be affected, increasing pollutant concentrations. This results in difficulties for the current treatment system and non-compliance occurrences.
Environmental Impact, j = 3	Fish incidents (i=5) $y_{i,j} = y_{5,3}$	Number of incidents involving fish mortality and/or stranding (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of incidents involving fish mortality. For instance, in prolonged drought conditions, water quality may be affected, intensifying eutrophication. This results in fish mortality and incident occurrences.
Environmental Impact, j = 3	Water quality (i=6) $y_{i,j} = y_{6,3}$	Water quality affects environmental, economic, and social interests while also impacting or hindering water use. This indicator evaluates the total nitrogen parameter (Ref.4).	The higher the intensity and duration of climate instability, the greater the impact on the total nitrogen water quality parameter. For example, in prolonged drought conditions, water quality may be affected, increasing total nitrogen concentrations.

Ref.1, Ref.4 adapted from [1], [4], respectively.

Figure S2.1b. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Environmental Impact, j = 3	Water quality (i=7) $y_{i,j} = y_{7,3}$	Water quality affects environmental, economic, and social interests while also impacting or hindering water use. This indicator evaluates the total phosphorus parameter (Ref.4).	The higher the intensity and duration of climate instability, the greater the impact on the total phosphorus water quality parameter. For example, in prolonged drought conditions, water quality may be affected, increasing total phosphorus concentrations.
Environmental Impact, j = 3	Failure of hydrodynamic and water quality model (i=8) $y_{i,j} = y_{8,3}$	This indicator applies to cases where the plant operation uses a hydrodynamic and water quality model. The extent of uncertainty depends on the quality of the data and the nature of the model (Ref.5). The occurrence of unforeseen events during model calibration may generate uncertainty.	The higher the intensity and duration of climate instability, the greater the impact on the quality of results from the hydrodynamic and water quality model. For example, in prolonged rainfall conditions, sediment transport into the reservoir may occur, resulting in failures in the hydrodynamic model results.
Safety, j = 4	Number of accidents with absence, also known as the accident frequency rate (i=1) $y_{i,j} = y_{1,4}$	Indicates the frequency of accidents with absence over a given period (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of accidents with absence. For example, during prolonged rainfall conditions, O&M activities are intensified, creating opportunities for accidents with absence.
Safety, j = 4	Number of days absent due to a work-related accident, also known as the accident severity rate (i=2) $y_{i,j} = y_{2,4}$	Indicates the severity of work-related accidents and/or the number of deaths resulting from injuries (Ref.1).	The higher the intensity and duration of climate instability, the longer the period of absence will be. For example, during prolonged rainfall conditions, O&M activities are intensified, creating an environment conducive to more severe accidents and longer periods of absence.
Safety, j = 4	Number of high-risk incidents (i=3) $y_{i,j} = y_{3,4}$	A hazardous situation in which the planned safety systems have proven inadequate or ineffective, and whose consequences could reasonably have led to a serious accident had the sequence of events not been interrupted by other means (Ref.6).	The higher the intensity and duration of climate instability, the greater the number of high-risk incidents. For example, during prolonged rainfall conditions, O&M activities are intensified, creating an environment conducive to high-risk incidents.
Safety, j = 4	Number of safety issues recorded per month (i=4) $y_{i,j} = y_{4,4}$	Number of fires, explosions, or safety issues recorded per month (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of safety issues recorded. For example, during prolonged rainfall conditions, O&M activities are intensified, resulting in more recorded safety issues.
Safety, j = 4	Number of road traffic accidents (i=5) $y_{i,j} = y_{5,4}$	Number of road traffic accidents on access roads and within the project's premises (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of road traffic accidents. For example, during prolonged rainfall conditions, O&M activities are intensified, leading to more opportunities for road traffic accidents.
Safety, j = 4	Number of near-miss incidents (i=6) $y_{i,j} = y_{6,4}$	Number of near-miss incidents reported (Ref.1).	The higher the intensity and duration of climate instability, the greater the number of near-miss incidents. For example, during prolonged rainfall conditions, O&M activities are intensified, creating opportunities for near-miss incidents.

Ref.1, Ref.4-Ref.6 adapted from [1], [4], [5], [6], respectively.

Figure S2.1c. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Safety, j = 4	Number of visits by team supervisors (i=7) $y_{i,j} = y_{7,4}$	Percentage of workplace visits conducted by team supervisors (Ref.1).	The higher the intensity and duration of climate instability, the greater the percentage of workplace (field) visits by supervisors. For example, during prolonged rainfall conditions, intensified and atypical O&M activities require greater involvement of team supervisors.
Safety, j = 4	Safety training programme (i=8) $y_{i,j} = y_{8,4}$	Team participation in safety meetings (Ref.1).	The higher the intensity and duration of climate instability, the greater the participation of employees in training programmes. For example, during prolonged rainfall conditions, intensified and atypical O&M activities necessitate safety training programmes with widespread employee participation.
Safety, j = 4	Preventive action (i=9) $y_{i,j} = y_{9,4}$	Implementation of recommendations from accident investigations (Ref.1).	The higher the intensity and duration of climate instability, the greater the implementation of preventive actions. For example, during prolonged rainfall conditions, intensified and atypical O&M activities make the implementation of preventive actions necessary and imperative.
Relations with Communities and Employees, j = 5	Civil society claims (i=1) $y_{i,j} = y_{1,5}$	Number of complaints filed by local communities and NGOs (Ref.1).	The higher the intensity and duration of climate instability, the more claims will arise from society. For example, during prolonged rainfall conditions, issues related to dam and reservoir safety are common. Similarly, during prolonged drought conditions, concerns about changes in water quality and the hydrological regime are common, resulting in more claims from civil society.
Relations with Communities and Employees, j = 5	Organised visits for the local community (i=2) $y_{i,j} = y_{2,5}$	Number of organised visits for the local Community (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in hosting visits. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions limits the interest in receiving visits from the community.
Relations with Communities and Employees, j = 5	Charity actions (i=3) $y_{i,j} = y_{3,5}$	Number of benefit-sharing actions for the local community (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in charity actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces the interest in charity actions.

Ref.1 adapted from [1].

Figure S2.1d. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Relations with Communities and Employees, j = 5	Communication actions (i=4) $y_{i,j} = y_{4,5}$	Number of activities in which plant employees participated to promote communication with the local Community (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in communication actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces the interest in communication actions.
Relations with Communities and Employees, j = 5	Personal development (i=5) $y_{i,j} = y_{5,5}$	Percentage of employees with a personal development plan (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in personal development actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces interest in personal development. Employees are not encouraged to initiate the creation of a personal development plan.
Relations with Communities and Employees, j = 5	Performance evaluations (i=6) $y_{i,j} = y_{6,5}$	Percentage of completed performance evaluations (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in personal development actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces interest in personal development. Employees are not encouraged to complete the creation of a personal development plan.
Relations with Communities and Employees, j = 5	Personal goals achieved (i=7) $y_{i,j} = y_{7,5}$	Percentage of employees who achieved their development plan objectives (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in personal development actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces interest in personal development. Employees are not encouraged to meet personal development plan goals.
Relations with Communities and Employees, j = 5	Employee satisfaction (i=8) $y_{i,j} = y_{8,5}$	Employee satisfaction survey, staff satisfaction index (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in personal development actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces interest in personal development. Naturally, the lack of prioritisation of employees reduces overall team satisfaction.

Ref.1 adapted from [1].

Figure S2.1e. Entry data.

Performance area, j	Key Performance Indicator (KPI)	Description	Relationship with climate instability
Relations with Communities and Employees, j = 5	Employee retention (i=9) $y_{i,j} = y_{9,5}$	Average number of years an employee stays at the company (Ref.1).	The higher the intensity and duration of climate instability, the greater the interest in retaining employees. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions results in efforts to maintain experienced human resources in plant operations, reducing interest in people who are just beginning to learn (new employees).
Relations with Communities and Employees, j = 5	Lost days (i=10) $y_{i,j} = y_{10,5}$	Number of days lost due to strikes or labour actions (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in lost days. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions results in efforts to prevent lost days.
Operation & Maintenance, j = 6	Cavitation and noise (i=1) $y_{i,j} = y_{1,6}$	Cavitation is a common flow phenomenon in most hydraulic turbines and has the potential to cause vibration, blade surface damage, and loss of performance (Ref.7).	The greater the intensity and duration of climate instability, the greater the negative effect of cavitation on the turbine. For example, during prolonged drought conditions, facilities are exposed to extreme conditions, reducing equipment lifespan, performance, among other factors.
Operation & Maintenance, j = 6	Silt erosion problems (i=2) $y_{i,j} = y_{2,6}$	It is a process of slow and continuous removal of material from the surface of mechanical components (Ref.8).	The greater the intensity and duration of climate instability, the greater the negative effect of silt erosion. For example, during prolonged rainfall conditions, sediment may be dragged into reservoirs, generating deposits and subsequently causing erosion of equipment due to silt.
Operation & Maintenance, j = 6	Fatigue wear (i=3) $y_{i,j} = y_{3,6}$	A process that weakens the material due to repeated cyclical stresses (Ref.8).	The greater the intensity and duration of climate instability, the greater the negative effect of fatigue wear. For example, during prolonged drought conditions, facilities are exposed to extreme conditions, reducing equipment lifespan and performance, potentially leading to the need for intermittent operation (successive stopping and starting of equipment).

Ref.1, Ref.7, Ref.8 adapted from [1], [7], [8], respectively.

Figure S2.1f. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Operation & Maintenance, j = 6	Material defects (i=4) $y_{i,j} = y_{4,6}$	Material defects in turbines and other components are controlled during manufacturing, but at the time of installation, some material defects may also cause failures, leading to component breakdowns (Ref.8).	The greater the intensity and duration of climate instability, the greater the negative effect of material defects (partial compliance with design specifications). For example, during prolonged drought conditions, facilities are exposed to extreme conditions that require the equipment to perform at its maximum. At this point, material difficulties result in reduced lifespan, lower performance, other issues.
Operation & Maintenance, j = 6	Conditions of the canal and sedimentation basin (i=5) $y_{i,j} = y_{5,6}$	Presence of deformation or absence of cracks in the structure; suspended debris in the grid; water leakage; sediment accumulation in the sedimentation basin (Ref.9, Ref.10, Ref.11).	The greater the intensity and duration of climate instability, the greater the negative effect on the intake canal and the sedimentation basin. For example, during significant changes in water levels, the canal and sedimentation basin are required to resist deformation and sediment accumulation, often beyond the limits planned in the design. This naturally results in the need for adaptation (design adjustments) and increased O&M activities.
Operation & Maintenance, j = 6	Presence of plant debris in the canal (i=6) $y_{i,j} = y_{6,6}$	Reduction in the intake canal's capacity due to the blockage of free space in the grid caused by the presence of plant debris (Ref.9).	The greater the intensity and duration of climate instability, the greater the presence of plant debris in the canal. For example, during prolonged drought conditions, the process of eutrophication may increase plant production, resulting in more plant debris in the canal.
Operation & Maintenance, j = 6	Presence of plant debris in the intake chamber (i=7) $y_{i,j} = y_{7,6}$	Loss of capacity in the grid due to plant debris accumulated in the intake chamber (Ref.9).	The greater the intensity and duration of climate instability, the greater the presence of plant debris in the intake chamber. For example, during prolonged drought conditions, the process of eutrophication may increase plant production, resulting in more plant debris in the intake chamber.
Operation & Maintenance, j = 6	Imbalance between water availability and users, low available load (i=8) $y_{i,j} = y_{8,6}$	It is the desired water level for energy production, the normal level (Ref.12).	The greater the intensity and duration of climate instability, the greater the water imbalance between users. For example, during prolonged drought conditions, conflicts between water users (public supply, animal watering, agriculture, energy generation, etc.) will affect the normal water level.
Operation & Maintenance, j = 6	Difficulty in defining ecological flow and governance at the regulatory institution (i=9) $y_{i,j} = y_{9,6}$	Problems in determining the amount of water to be released into the streambed, as well as governance and authority within the organisation (Ref.12).	The greater the intensity and duration of climate instability, the greater the difficulty in defining ecological flow. For example, during prolonged drought conditions, conflicts between water users (public supply, animal watering, agriculture, energy generation, etc.) will affect the ecological flow to be considered.

Ref.9-Ref.12 adapted from [9], [10], [11], [12], respectively.

Figure S2.1g. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Operation & Maintenance, j = 6	Insufficiency of flow observation stations (i=10) $y_{i,j} = y_{10,6}$	The insufficiency of flow observation stations (FOS) results in operational difficulties, with improper operation at the correct stages and failures in functions (Ref.12).	The greater the intensity and duration of climate instability, the greater the need for observation stations. For example, during prolonged rainfall conditions, the current number of observation stations may be insufficient, leading to a demand for new stations.
Operation & Maintenance, j = 6	Operation, repair, and revitalisation contracts not clearly defined, especially during periods of low water availability (i=11) $y_{i,j} = y_{11,6}$	Some hydropower plants attempt to refrain from signing an additional protocol, with a lower share of operational and maintenance costs due to low water availability (Ref.12).	The greater the intensity and duration of climate instability, the greater the difficulty in forecasting/planning O&M needs. For example, during prolonged drought conditions, the wear on parts/equipment that are traditionally underused may be intensified, requiring unforeseen O&M activities
Operation & Maintenance, j = 6	Inaccuracy in operational data, flow, pressure, and power (i=12) $y_{i,j} = y_{12,6}$	There are some difficulties associated with determining the turbine inlet flow, as well as determining power and water level (Ref.12).	The greater the intensity and duration of climate instability, the greater the difficulty in obtaining accurate flow, pressure, and/or power values. For example, during prolonged drought conditions, flow meters selected based on normal operational ranges may fail due to conditions different from those specified by the manufacturer.
Operation & Maintenance, j = 6	Deformation or cracking in the structure, blades, turbine shaft (i=13) $y_{i,j} = y_{13,6}$	A parameter that helps estimate the service life of hydraulic turbines (Ref.13).	The greater the intensity and duration of climate instability, the greater the structural demands on the equipment, which may lead to deformation problems. For example, during prolonged drought conditions, prolonged operation under extreme conditions may result in deformation or cracking of the structure, blades, or turbine shaft.
Operation & Maintenance, j = 6	Mechanical equipment damage, instability (i=14) $y_{i,j} = y_{14,6}$	Vibration, pressure pulsations, and hydrodynamic instability in the turbine (Ref.14).	The greater the intensity and duration of climate instability, the greater the structural demands on the equipment, as well as the manifestation of instability through vibration. For example, during prolonged drought conditions, prolonged operation under extreme conditions places stress on the equipment, resulting in vibration.
Operation & Maintenance, j = 6	Reduction in capacity and generation (i=15) $y_{i,j} = y_{15,6}$	Reduction in the production capacity of hydroelectric plants, efficiency decline (Ref.15).	The greater the intensity and duration of climate instability, the greater the reduction in generation. For example, during prolonged drought conditions, prolonged operation under extreme conditions wears out equipment and reduces its efficiency.
Operation & Maintenance, j = 6	Spillway overflow (i=16) $y_{i,j} = y_{16,6}$	There are defects in spillway, drainage, and discharge gate installations (Ref.11).	The greater the intensity and duration of climate instability, the greater the damage to spillway installations. For example, during prolonged rainfall conditions, spillway structures are stressed to their limits and may be damaged.

Ref.11-Ref.15 adapted from [11], [12], [13], [14], [15], respectively.

Figure S2.1h. Entry data.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Operation & Maintenance, j = 6	Risk of generation interruption (i=17) $y_{ij} = y_{17,6}$	Risk of shutdown in the operation of the generating unit (Ref.15).	The greater the intensity and duration of climate instability, the greater the risk of generation interruption. For example, during prolonged drought conditions, low water levels increase the risk of generation interruption.
Operation & Maintenance, j = 6	Exceeding the design flood flow, spillway (i=18) $y_{ij} = y_{18,6}$	Probability of dam overflow caused by hydraulic and hydrological events (Ref.15).	The greater the intensity and duration of climate instability, the greater the risk of exceeding the design flood flow. For example, during prolonged rainfall conditions, high water levels may surpass the values predicted in the design, creating risks and serious operational issues.

Ref.15 adapted from [15].

Figure S2.1i. Entry data.

The calculation equations of $x_{i,j}$, the parameters of $x_{i,j,k}^L$ and $x_{i,j,k}^U$, and the theoretical framework are shown in Figure SMP2.2a, SMP2.2b, ..., SMP2.2h.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
1	1	1	0.0	10.0	0.1	$x_{1,1} = \frac{\text{O\&M expenses}}{\text{O\&M budget}} \cdot 100$ Where: expenses and budget for O&M are expressed in 10^3 R\$. Scale: 0.1 to 1.1; 1 is the no impact, 1.1 is the Strong impact. Source: adapted scale from (Ref.1).	(Ref.1)
1	1	2	10.1	20.0	0.2		
1	1	3	20.1	30.0	0.3		
1	1	4	30.1	40.0	0.4		
1	1	5	40.1	60.0	0.5		
1	1	6	60.1	80.0	0.6		
1	1	7	80.1	100.0	0.7		
1	1	8	100.1	120.0	0.8		
1	1	9	120.1	140.0	0.9		
1	1	10	140.1	160.0	1.0		
1	1	11	160.1	>160.1	1.1		
1	2	1	0.0	10.0	0.1	$x_{2,1} = \frac{\text{capital expenditure cost}}{\text{capital expenditure budget}} \cdot 100$ Where: the cost and budget for capital expenses are expressed in 10^3 R\$. Scale: 0.1 to 1.1; 0.1 represents no impact, 1.1 represents a strong impact. Source: scale adapted from (Ref.1).	(Ref.1)
1	2	2	10.1	20.0	0.2		
1	2	3	20.1	30.0	0.3		
1	2	4	30.1	40.0	0.4		
1	2	5	40.1	60.0	0.5		
1	2	6	60.1	80.0	0.6		
1	2	7	80.1	100.0	0.7		
1	2	8	100.1	120.0	0.8		
1	2	9	120.1	140.0	0.9		
1	2	10	140.1	160.0	1.0		
1	2	11	160.1	>160.1	1.1		
1	3	1	0.0	10.0	0.1	$x_{3,1} = \frac{\text{special maintenance cost}}{\text{special maintenance budget}} \cdot 100$ Where: the cost and budget for special maintenance are expressed in 10^3 R\$. Scale: 0.1 to 1.1; 0.1 represents no impact, 1.1 represents a strong impact. Source: scale adapted from (Ref.1).	(Ref.1)
1	3	2	10.1	20.0	0.2		
1	3	3	20.1	30.0	0.3		
1	3	4	30.1	40.0	0.4		
1	3	5	40.1	60.0	0.5		
1	3	6	60.1	80.0	0.6		
1	3	7	80.1	100.0	0.7		
1	3	8	100.1	120.0	0.8		
1	3	9	120.1	140.0	0.9		
1	3	10	140.1	160.0	1.0		
1	3	11	160.1	>160.1	1.1		

Ref.1, Ref.2 adapted from [1], [2], respectively.

Figure S2.2a. Parameters of the general equation for $KPI_{i,j}$ indicators.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
2	2	1	0.00	0.10	0.1	$x_{2,2} = \frac{x_{22,1}}{x_{22,2}}$ Where: $x_{22,1}$ is the verified availability index; $x_{22,2}$ is the reference availability index. Scale: 0.1 to 1; 0.1 represents a strong impact, 1.0 represents no impact. Source: scale adapted from (Ref.3).	(Ref.3)
2	2	2	0.11	0.20	0.2		
2	2	3	0.21	0.40	0.3		
2	2	4	0.41	0.60	0.4		
2	2	5	0.61	0.80	0.5		
2	2	6	0.81	0.90	0.6		
2	2	7	0.91	>0.91	1.0		
2	3	1	0.90	1.00	0.1	$x_{3,2} = \frac{x_{32,1}}{x_{32,2}}$ Where: $x_{32,1}$ is the number of interruptions for completed preventive maintenance; $x_{32,2}$ is the number of interruptions for planned preventive maintenance. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.2).	(Ref.1, Ref.2)
2	3	2	1.01	1.10	0.2		
2	3	3	1.11	1.20	0.3		
2	3	4	1.21	1.30	0.4		
2	3	5	1.31	1.40	0.5		
2	3	6	1.41	1.50	0.6		
2	3	7	1.51	1.60	0.7		
2	3	8	1.61	1.70	0.8		
2	3	9	1.71	1.80	0.9		
2	3	10	1.81	>1.81	1.0		
2	4	1	0.0	10.0	0.1	$x_{4,2} = \frac{x_{42,1}}{x_{42,2}} \cdot 100$ Where: $x_{42,1}$ is the number of emergency O&M hours; $x_{42,2}$ is the total number of O&M hours. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.2).	(Ref.1, Ref.2)
2	4	2	10.1	20.0	0.2		
2	4	3	20.1	30.0	0.3		
2	4	4	30.1	40.0	0.4		
2	4	5	40.1	50.0	0.5		
2	4	6	50.1	60.0	0.6		
2	4	7	60.1	70.0	0.7		
2	4	8	70.1	80.0	0.8		
2	4	9	80.1	90.0	0.9		
2	4	10	90.1	100.0	1.0		
2	5	1	0.0	10.0	0.1	$x_{5,2} = \frac{x_{52,1}}{x_{52,2}} \cdot 100$ Where: $x_{52,1}$ is the volume of water discharged, m ³ ; $x_{52,2}$ is the volume of water entering the plant in m ³ . Scale: 0.1 to 1.0; 0.1 represents a strong impact, 1.0 represents no impact. Source: scale adapted from (Ref.1).	(Ref.1)
2	5	2	10.1	20.0	0.2		
2	5	3	20.1	30.0	0.3		
2	5	4	30.1	40.0	0.4		
2	5	5	40.1	50.0	0.5		
2	5	6	50.1	60.0	0.6		
2	5	7	60.1	70.0	0.7		
2	5	8	70.1	80.0	0.8		
2	5	9	80.1	90.0	0.9		
2	5	10	90.1	100.0	1.0		
2	6	1	0.0	10.0	0.1	$x_{6,2} = \frac{\text{Generated energy}}{\text{Generation capacity}} \cdot 100$ Scale: 0.1 to 1.0; 0.1 represents a strong impact, 1.0 represents no impact. Source: scale adapted from (Ref.1).	(Ref.1)
2	6	2	10.1	20.0	0.2		
2	6	3	20.1	30.0	0.3		
2	6	4	30.1	40.0	0.4		
2	6	5	40.1	50.0	0.5		
2	6	6	50.1	60.0	0.6		
2	6	7	60.1	70.0	0.7		
2	6	8	70.1	80.0	0.8		
2	6	9	80.1	90.0	0.9		
2	6	10	90.1	100.0	1.0		
3	1	1	0	0	0.1	Where: $x_{1,3}$ is the number of incidents of non-compliance with the ecological flow. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.1).	(Ref.1)
3	1	2	1.0	2.0	0.2		
3	1	3	2.1	4.0	0.5		
3	1	4	4.1	6.0	0.8		
3	1	5	6.1	>6.1	1.0		
3	2	1	0	0	0.1	Where: x_{23} is the number of pollutant discharge incidents. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.1).	(Ref.1)
3	2	2	1.0	2.0	0.2		
3	2	3	2.1	4.0	0.5		
3	2	4	4.1	6.0	0.8		
3	2	5	6.1	>6.1	1.0		

Ref.1-Ref.3 adapted from [1], [2], [3], respectively.

Figure S2.2b. Parameters of the general equation for KPI_{ij} indicators.

Performance area, j	Key Performance Indicator (KPIi)	Description	Relationship with climate instability
Safety, j = 4	Number of visits by team supervisors (i=7) $y_{i,j} = y_{7,4}$	Percentage of workplace visits conducted by team supervisors (Ref.1).	The higher the intensity and duration of climate instability, the greater the percentage of workplace (field) visits by supervisors. For example, during prolonged rainfall conditions, intensified and atypical O&M activities require greater involvement of team supervisors.
Safety, j = 4	Safety training programme (i=8) $y_{i,j} = y_{8,4}$	Team participation in safety meetings (Ref.1).	The higher the intensity and duration of climate instability, the greater the participation of employees in training programmes. For example, during prolonged rainfall conditions, intensified and atypical O&M activities necessitate safety training programmes with widespread employee participation.
Safety, j = 4	Preventive action (i=9) $y_{i,j} = y_{9,4}$	Implementation of recommendations from accident investigations (Ref.1).	The higher the intensity and duration of climate instability, the greater the implementation of preventive actions. For example, during prolonged rainfall conditions, intensified and atypical O&M activities make the implementation of preventive actions necessary and imperative.
Relations with Communities and Employees, j = 5	Civil society claims (i=1) $y_{i,j} = y_{1,5}$	Number of complaints filed by local communities and NGOs (Ref.1).	The higher the intensity and duration of climate instability, the more claims will arise from society. For example, during prolonged rainfall conditions, issues related to dam and reservoir safety are common. Similarly, during prolonged drought conditions, concerns about changes in water quality and the hydrological regime are common, resulting in more claims from civil society.
Relations with Communities and Employees, j = 5	Organised visits for the local community (i=2) $y_{i,j} = y_{2,5}$	Number of organised visits for the local Community (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in hosting visits. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions limits the interest in receiving visits from the community.
Relations with Communities and Employees, j = 5	Charity actions (i=3) $y_{i,j} = y_{3,5}$	Number of benefit-sharing actions for the local community (Ref.1).	The higher the intensity and duration of climate instability, the less interest there will be in charity actions. For example, during prolonged rainfall or drought conditions, facilities are exposed to extreme conditions. The prioritisation of responding appropriately to these conditions reduces the interest in charity actions.

Ref.1, Ref.4, Ref.6, Ref.15-Ref.20 adapted from [1], [4], [6], [15], [16], [17], [18], [19], [20], respectively.

Figure S2.2c. Parameters of the general equation for $KPI_{i,j}$ indicators.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
4	6	1	0	0	0.2	Where: x_{64} is a near miss (close call).	(Ref.1)
4	6	2	1	2	0.4	Scale: 1 to 5; 1 represents no impact, 5 represents a strong impact.	
4	6	3	3	4	0.6	Source: scale adapted from (Ref.6).	
4	6	4	5	6	0.8		
4	6	5	7	>7	1.0		(Ref.1)
4	7	1	0.0	20.0	0.1	$x_{7,4} = \frac{x_{74,1}}{x_{74,2}} \cdot 100$	
4	7	2	20.1	40.0	0.4	Where: $x_{74,1}$ is the number of visits conducted with the participation of the team supervisor; $x_{74,2}$ is the total number of visits conducted.	
4	7	3	40.1	60.0	0.6	Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact.	
4	7	4	60.1	80.0	0.8	Source: scale adapted from (Ref.1).	
4	7	5	80.1	100.0	1.0		(Ref.1)
4	8	1	0.0	20.0	0.1	$x_{8,4} = \frac{x_{84,1}}{x_{84,2}} \cdot 100$	
4	8	2	20.1	40.0	0.4	Where: $x_{84,1}$ is the total number of operation team members; $x_{84,2}$ is the number of operation team members who participated in the safety training program.	
4	8	3	40.1	60.0	0.6	Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact.	
4	8	4	60.1	80.0	0.8	Source: scale adapted from (Ref.1).	
4	8	5	80.1	100.0	1.0		(Ref.1)
4	9	1	0.0	20.0	0.1	$x_{9,4} = \frac{x_{94,1}}{x_{94,2}} \cdot 100$	
4	9	2	20.1	40.0	0.4	Where: $x_{94,1}$ is the number of accident prevention recommendations implemented; $x_{94,2}$ is the total number of accident prevention recommendations.	
4	9	3	40.1	60.0	0.6	Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact.	
4	9	4	60.1	80.0	0.8	Source: scale adapted from (Ref.1).	
4	9	5	80.1	100.0	1.0		(Ref.1)
5	1	1	0	0	0.1	Where: $x_{1,5}$ is claims and complaints received from the local community.	
5	1	2	1	20	0.4	Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact.	
5	1	3	21	40	0.6	Source: scale adapted from (Ref.1).	
5	1	4	41	60	0.8		
5	1	5	61	>61	1.0		(Ref.1)
5	2	1	0	0	0.1	Where: $x_{2,5}$ is the increase in the number of community visits to the plant.	
5	2	2	1	10	0.4	Scale: 0.1 to 1.0; 0.1 represents a strong impact, 1.0 represents no impact.	
5	2	3	11	20	0.6	Source: scale adapted from (Ref.1).	
5	2	4	21	30	0.8		
5	2	5	31	>31	1.0		(Ref.1)
5	3	1	0	0	0.1	Where: $x_{3,5}$ are actions of benefit distribution.	
5	3	2	1	2	0.2	Scale: 0.1 to 0.7; 0.1 represents a strong impact, 0.7 represents no impact.	
5	3	3	3	4	0.3	Source: scale adapted from (Ref.1).	
5	3	4	5	6	0.4		
5	3	5	7	8	0.5		(Ref.1)
5	3	6	9	10	0.6		
5	3	7	11	>11	0.7		
5	4	1	0	0	0.1	Where: $x_{4,5}$ is the increase in communication actions that employees participate in.	
5	4	2	1	2	0.2	Scale: 0.1 to 0.7; 0.1 represents a strong impact, 0.7 represents no impact.	
5	4	3	3	4	0.3	Source: scale adapted from (Ref.1).	
5	4	4	5	6	0.4		
5	4	5	7	8	0.5		
5	4	6	9	10	0.6		
5	4	7	11	>11	0.7		

Ref.1 adapted from [1]

Figure S2.2d. Parameters of the general equation for $KPI_{i,j}$ indicators.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
5	5	1	0.0	5.0	0.1	$x_{5,5} = \frac{x_{55,1}}{x_{55,2}} \cdot 100$ Where: $x_{55,1}$ is the number of new employees with a development plan; $x_{55,2}$ is the total number of employees. Scale: 0.1 to 1.1; 0.1 represents a strong impact, 1.1 represents no impact. Source: scale adapted from (Ref.1).	(Ref.1)
5	5	2	5.1	10.0	0.2		
5	5	3	10.1	20.0	0.3		
5	5	4	20.1	30.0	0.4		
5	5	5	30.1	40.0	0.5		
5	5	6	40.1	50.0	0.6		
5	5	7	50.1	60.0	0.7		
5	5	8	60.1	70.0	0.8		
5	5	9	70.1	80.0	0.9		
5	5	10	80.1	90.0	1.0		
5	5	11	90.1	100.0	1.1		
5	6	1	0.0	5.0	0.1	$x_{6,5} = \frac{x_{65,1}}{x_{65,2}} \cdot 100$ Where: $x_{65,1}$ is the number of people with completed performance evaluations; $x_{65,2}$ is the total number of employees. Scale: 0.1 to 1.1; 0.1 represents a strong impact, 1.1 represents no impact. Source: scale adapted from (Ref.1).	(Ref.1)
5	6	2	5.1	10.0	0.2		
5	6	3	10.1	20.0	0.3		
5	6	4	20.1	30.0	0.4		
5	6	5	30.1	40.0	0.5		
5	6	6	40.1	50.0	0.6		
5	6	7	50.1	60.0	0.7		
5	6	8	60.1	70.0	0.8		
5	6	9	70.1	80.0	0.9		
5	6	10	80.1	90.0	1.0		
5	6	11	90.1	100.0	1.1		
5	7	1	0.0	5.0	0.1	$x_{7,5} = \frac{x_{75,1}}{x_{75,2}} \cdot 100$ Where: $x_{75,1}$ is the number of people with achieved goals; $x_{75,2}$ is the total number of employees. Scale: 0.1 to 1.1; 0.1 represents a strong impact, 1.1 represents no impact. Source: scale adapted from (Ref.1).	(Ref.1)
5	7	2	5.1	10.0	0.2		
5	7	3	10.1	20.0	0.3		
5	7	4	20.1	30.0	0.4		
5	7	5	30.1	40.0	0.5		
5	7	6	40.1	50.0	0.6		
5	7	7	50.1	60.0	0.7		
5	7	8	60.1	70.0	0.8		
5	7	9	70.1	80.0	0.9		
5	7	10	80.1	90.0	1.0		
5	7	11	90.1	100.0	1.1		
5	8	1	0.0	5.0	0.1	$x_{8,5} = \frac{x_{85,1}}{x_{85,2}} \cdot 100$ Where: $x_{85,1}$ is the number of satisfied employees; $x_{85,2}$ is the total number of employees. Scale: 0.1 to 1.1; 0.1 represents a strong impact, 1.1 represents no impact. Source: scale adapted from (Ref.1).	(Ref.1)
5	8	2	5.1	10.0	0.2		
5	8	3	10.1	20.0	0.3		
5	8	4	20.1	30.0	0.4		
5	8	5	30.1	40.0	0.5		
5	8	6	40.1	50.0	0.6		
5	8	7	50.1	60.0	0.7		
5	8	8	60.1	70.0	0.8		
5	8	9	70.1	80.0	0.9		
5	8	10	80.1	90.0	1.0		
5	8	11	90.1	100.0	1.1		
5	9	1	0	3	0.1	Where: $x_{9,5}$ is the average number of years. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.1).	(Ref.1)
5	9	2	4	6	0.2		
5	9	3	7	9	0.5		
5	9	4	10	12	0.8		
5	9	5	13	>13	1.0	Where: $x_{10,5}$ is the number of days lost due to strikes or labor actions. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.1).	(Ref.1)
5	10	1	0	0	0.1		
5	10	2	1	5	0.2		
5	10	3	6	10	0.3		
5	10	4	11	15	0.5		
5	10	5	16	20	0.8		
6	1	1	1	1	0.1	Where: $x_{1,6}$ is the type of cavitation and noise; 1 is no occurrence; 2 is incipient occurrence; 3 is moderate cavitation occurrence; 4 is strong cavitation occurrence. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.21).	(Ref.8, Ref.21, Ref.22, Ref.23, Ref.24, Ref.25)
6	1	2	2	2	0.5		
6	1	3	3	3	0.8		
6	1	4	4	4	1.0		

Ref.1, Ref.8, Ref.10, Ref.12, Ref.14, Ref.16, Ref.21-Ref.34 adapted from [1], [8], [10], [12], [14], [16], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], respectively.

Figure S2.2e. Parameters of the general equation for KPI_{ij} indicators.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
6	2	1	1	1	0.1	Where: $x_{2,6}$ is the silt erosion problem; 1 is no silt erosion; 2 is polished metal; 3 is fine scales; 4 is surface with incrustation; 5 is deep scales; 6 is deep channels; 7 is holes in the material. Scale: 0.1 to 0.7; 0.1 represents no impact, 0.7 represents a strong impact. Source: scale adapted from (Ref.26).	(Ref.10, Ref.12, Ref.16, Ref.22, Ref.24, Ref.26, Ref.27, Ref.28, Ref.29, Ref.30)
6	2	2	2	2	0.2		
6	2	3	3	3	0.3		
6	2	4	4	4	0.4		
6	2	5	5	5	0.5		
6	2	6	6	6	0.6		
6	2	7	7	7	0.7		
6	3	1	0	0	0.1	Where: $x_{3,6}$ is the start-stop cycle, referred to as the fatigue cycle. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.31, Ref.32).	(Ref.14, Ref.22, Ref.24, Ref.25, Ref.33, Ref.34)
6	3	2	1	2	0.2		
6	3	3	3	4	0.3		
6	3	4	5	6	0.6		
6	3	5	7	8	0.8		
6	3	6	9	>9	1.0		
6	4	1	1	1	0.1	Where 1 is the case where the required design configuration was fully met and there are no difficulties related to moments of climatic instability; 2 is the case where the required design configuration was partially met and there are difficulties related to moments of climatic instability. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.8).	(Ref.8, Ref.24)
6	4	2	2	2	1.0		
6	5	1	1.0	2.0	0.1	$y_{5,6} = x_{56,1} + x_{56,2}$ $x_{56,1} = \begin{cases} 1, \text{ se } CB \text{ is } D_1 \\ 2, \text{ se } CB \text{ is } D_2 \\ 3, \text{ se } CB \text{ is } D_3 \\ 4, \text{ se } CB \text{ is } D_4 \\ 5, \text{ se } CB \text{ is } D_5 \\ 6, \text{ se } CB \text{ is } D_6 \\ 7, \text{ se } CB \text{ is } D_7 \end{cases}$ $x_{56,2} = \begin{cases} 0, \text{ se } BS \text{ is } A_2 \\ 0.5, \text{ se } BS \text{ is } B_2 \end{cases}$ Where: CB is the condition of the canal and sedimentation basin; D1 is the absence of deformation (construction pathology); D2 is the presence of cracks, fissures, and fractures; D3 is the presence of infiltration; D4 is the presence of stains; D5 is the presence of efflorescence; D6 is the presence of corrosion of reinforcements; D7 is the presence of concrete deterioration; BS is the operational condition of the sedimentation basin; A1 is no sediment accumulation; A2 is sediment accumulation. Scale: 0.1 to 0.7; 0.1 represents no impact, 0.7 represents a strong impact. Source: scale adapted from (Ref. 9, Ref.10, Ref.11, Ref.35).	(Ref.9, Ref.10, Ref.11)
6	5	2	2.1	3.0	0.2		
6	5	3	3.1	4.0	0.3		
6	5	4	4.1	5.0	0.4		
6	5	5	5.1	6.0	0.5		
6	5	6	6.1	7.0	0.6		
6	5	7	7.1	>7.1	0.7		
6	6	1	0	10.0	0.1	Where: $x_{6,6}$ is the percentage of obstruction of the cross-sectional area of the grate, due to the presence of plant debris in the channel at the inlet grate. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.9).	(Ref.1, Ref.9, Ref.24)
6	6	2	10.1	20.0	0.2		
6	6	3	20.1	30.0	0.3		
6	6	4	30.1	40.0	0.6		
6	6	5	40.1	50.0	0.8		
6	6	6	50.1	>50.1	1.0		
6	7	1	0	10.0	0.1	Where: $x_{7,6}$ is the percentage of obstruction of the cross-sectional area of the grate, due to the presence of plant debris in the grate at the inlet of the intake chamber. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from [9].	(Ref.9)
6	7	2	10.1	20.0	0.2		
6	7	3	20.1	30.0	0.3		
6	7	4	30.1	40.0	0.6		
6	7	5	40.1	50.0	0.8		
6	7	6	50.1	>50.1	1.0		

Ref.1, Ref.8-Ref.12, Ref.16, Ref.24, Ref.35-Ref.37 adapted from [1], [8], [9], [10], [11], [12], [16], [24], [35], [36], [37], respectively.

Figure S2.2f. Parameters of the general equation for $KPI_{i,j}$ indicators.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
6	8	1	100.1	110.0	0.1	Where: $x_{8,6}$ is the operational condition in relation to the normal water level. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adopted from [36].	(Ref.1, Ref.12, Ref.16, Ref.36, Ref.37)
6	8	2	90.1	100.0	0.2		
6	8	3	80.1	90.0	0.3		
6	8	4	70.1	80.0	0.6		
6	8	5	60.1	70.0	0.8		
6	8	6	<60.0	60.0	1.0		
6	9	1	1	1	0.1	Where: $x_{9,6}$ is the difficulty encountered; 1: there is a clear definition of the ecological flow and the regulatory institution is excellently organized; 2: there is uncertainty about the ecological flow and the regulatory institution has a reasonable organization; 3: there is no definition of the ecological flow and the regulatory institution is poorly organized. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.12).	(Ref.12, Ref.16)
6	9	2	2	2	0.5		
6	9	3	3	3	1.0		
6	10	1	1	1	0.1	Where: $x_{10,6}$ is the condition of the FOS (likely referring to a specific system or parameter); 1: sufficient condition; 2: moderately sufficient condition; 3: poor and imprecise condition; 4: insufficient and disordered condition. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.12).	(Ref.12, Ref.16)
6	10	2	2	2	0.3		
6	10	3	3	3	0.6		
6	10	4	4	4	1.0		
6	11	1	1	1	0.1	Where: $x_{11,6}$ refers to operation, repair, and revitalization contracts; 1: the clauses of the water use contract regarding operation, repair, and restoration expenses are adequately observed; 2: the clauses of the water use contract regarding operation, repair, and restoration expenses are not adequately observed. Scale: 1 to 2; 1 represents no impact, 2 represents a strong impact. Source: scale adapted from (Ref.12).	(Ref.12)
6	11	2	2	2	1.0		
6	12	1	0.0	5.0	0.1	Where: $x_{12,6}$ is the percentage of imprecision in flow, pressure, or power data. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.12).	(Ref.12)
6	12	2	5.1	10.0	0.2		
6	12	3	10.1	15.0	0.5		
6	12	4	15.1	20.0	0.8		
6	12	5	20.1	>20.1	1.0		
6	13	1	1	1	0.1	Where: $x_{13,6}$ is the deformation observed during a period of climatic instability; 1: no deformation or crack in the structure; 2: corrosion on the shaft; 3: multiple fatigue cracks on the shaft; 4: non-dangerous crack on the blade; 5: moderately dangerous crack on the blade; 6: dangerous crack on the blade; 7: combinations of previous items. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.13, Ref.24).	(Ref.13, Ref.34)
6	13	2	2	2	0.2		
6	13	3	3	3	0.3		
6	13	4	4	4	0.4		
6	13	5	5	5	0.5		
6	13	6	6	6	0.6		
6	13	7	7	7	0.7		
6	14	1	1	1	0.1	Where: $x_{14,6}$ is the instability in the equipment; 1: no vibration; 2: incipient vibration; 3: moderate vibration; 4: strong vibration. Scale: 0.1 to 1.0; 0.1 represents no impact, 1.0 represents a strong impact. Source: scale adapted from (Ref.21).	(Ref.10, Ref.14, Ref.15, Ref.21, Ref.23, Ref.24, Ref.25, Ref.33, Ref.34, Ref.38)
6	14	2	2	2	0.3		
6	14	3	3	3	0.7		
6	14	4	4	4	1.0		

Ref.10-Ref.16, Ref.21, Ref.23-Ref.25, Ref.33, Ref.34, Ref.38 adapted from [10], [11], [12], [13], [14], [15], [21], [23], [24], [25], [33], [34], [38], respectively.

Figure S2.2g. Parameters of the general equation for KPI_{ij} indicators.

j	i	k	$x_{i,j,k}^L$	$x_{i,j,k}^U$	$g_{i,j,k}$	Calculation equations	Reference
6	15	1	0.0	1.0	0.1	Where: $x_{15,6}$ represents the percentage decrease in efficiency. Scale: 0.1 to 0.7; 0.1 indicates no impact, while 0.7 indicates a significant impact. Source: Scale adapted from (Ref.15).	(Ref.14, Ref.15)
6	15	2	1.1	2.0	0.2		
6	15	3	2.1	4.0	0.3		
6	15	4	4.1	6.0	0.4		
6	15	5	6.1	8.0	0.5		
6	15	6	8.1	10.0	0.6		
6	15	7	10.1	>10.1	0.7	Where: $x_{16,6}$ represents the overflow installation/condition; 1: undamaged installation; 2: flood relief channels are damaged; 3: overflow structure has abnormal cracks; 4: energy dissipation devices are damaged; 5: presence of settlements and water infiltration in the base slabs and side walls of spillways and flood tunnels; 6: combinations of the previous items. Scale: 0.1 to 0.6; 0.1 indicates no impact, while 0.6 indicates a significant impact. Source: Scale adapted from (Ref.11).	(Ref.10, Ref.11)
6	16	1	1	1	0.1		
6	16	2	2	2	0.2		
6	16	3	3	3	0.3		
6	16	4	4	4	0.4		
6	16	5	5	5	0.5		
6	16	6	6	6	0.6		
6	17	1	1	1	0.1	Where: $x_{17,6}$ represents the risk of generation interruption; 1: no risk; 2: risk of limiting the operation of a unit; 3: existing failures in the operation of the unit. Scale: 1 to 3; 1 indicates no impact, while 3 indicates a significant impact. Source: Scale adapted from (Ref.14).	(Ref.14, Ref.15)
6	17	2	2	2	0.5		
6	17	3	3	3	1.0		
6	18	1	0.00	0.05	0.1	Where: $x_{18,6}$ represents the probability of exceeding the spillway design flow during a period of climatic instability; very unlikely, probability of occurrence from 0.00 to 0.05; highly unlikely, probability of occurrence from 0.06 to 0.10; quite unlikely, probability of occurrence from 0.11 to 0.20; unlikely, probability of occurrence from 0.21 to 0.48; equal probability of occurrence and non-occurrence, probability of occurrence from 0.49 to 0.51; likely, probability of occurrence from 0.52 to 0.65; quite likely, probability of occurrence from 0.66 to 0.80; highly likely, probability of occurrence from 0.81 to 0.90; very likely, probability of occurrence from 0.91 to 0.95; high occurrence potential, probability of occurrence from 0.96 to 1.00. Scale: 0.1 to 0.9; 0.1 indicates no impact, while 0.9 indicates a significant impact. Source: Scale adapted from (Ref.39).	(Ref.15, Ref.39, Ref.40)
6	18	2	0.06	0.10	0.2		
6	18	3	0.11	0.20	0.3		
6	18	4	0.21	0.48	0.4		
6	18	5	0.49	0.51	0.5		
6	18	6	0.52	0.65	0.6		
6	18	7	0.66	0.80	0.7		
6	18	8	0.81	0.90	0.8		
6	18	9	0.91	0.95	0.9		
6	18	10	0.96	1.00	1.0		

Ref.14, Ref.15, Ref.39, Ref.40 adapted from [14], [15], [39], [40], respectively.

Figure S2.2h. Parameters of the general equation for $KPI_{i,j}$ indicators.

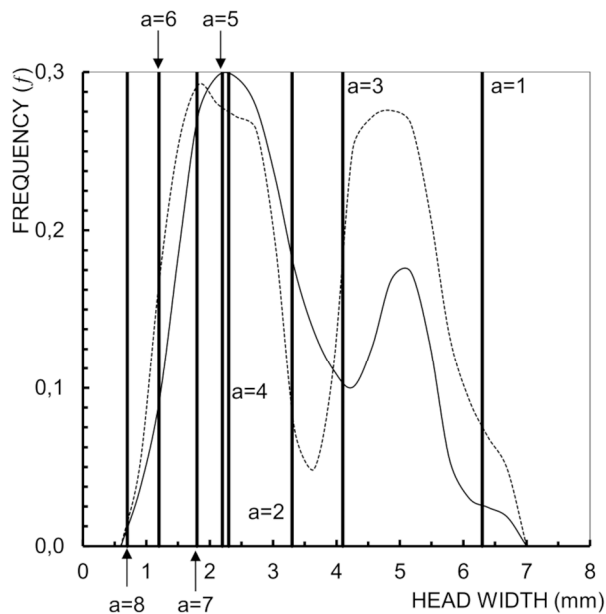
S2-2. Calculation of the importance values (weights) of castes

The description of the calculations for the importance values of each caste is presented below. The demographic data for both the new and old colonies of *Atta cephalotes* ants was obtained according to the literature [41]. The demographic data includes a curve showing frequency (ranging from 0 to 0.3), ant head size (ranging from 0.6 to 6.0 mm), and colony age, as described in [41]. The head size for each caste was obtained from the literature, as shown in Table SMP2.1. A summary of the obtained information can be found in Figure SMP2.3.

Table S2.1. Cast and head size, estimated from the literature [41].

Cast	Minimum size (mm)	Maximum size (mm)	Average size (mm)
Queen, $a = 1$	5.6	7.0	6.3
Male, $a = 2$	1.6	5.0	3.3
W. soldier, $a = 3$	2.6	5.6	4.1
W. foraging, $a = 4$	1.8	2.8	2.3
W. gardener, $a = 5$	2.0	2.4	2.2
W. nurse, $a = 6$	1.6	2.0	1.8
W. from nest, $a = 7$	0.8	1.6	1.2
W. pastoral, $a = 8$	0.6	0.8	0.7

NOTE: W. is worker.



NOTE: The solid line represents the new colony; the dashed line represents the old colony; $a = 1, 2, \dots, 8$ correspond to the castes queen, male, soldier worker, forager worker, gardener worker, nurse worker, nest worker, and pasture worker, respectively.

Figure S2.3. Adaptive demography of ant colony, estimated from the literature [41].

Consulting Figure SMP2.3 allows the estimation of population frequency for different ant head sizes. For example,

the head size entry of 1.2 mm (average for the nest worker, $a = 6$) in Figure SMP2.3 will yield frequencies of $f = 0.0900$ and $f = 0.1650$ for the young and old colonies, respectively. The values obtained for all worker castes are:

- $a = 3$, young colony $f = 0.1025$, old colony $f = 0.1825$;
- $a = 4$, young colony $f = 0.2990$, old colony $f = 0.2750$;
- $a = 5$, young colony $f = 0.3000$, old colony $f = 0.2775$;
- $a = 6$, young colony $f = 0.0900$, old colony $f = 0.1650$;
- $a = 7$, young colony $f = 0.2700$, old colony $f = 0.2935$;
- $a = 8$, young colony $f = 0.0100$, old colony $f = 0.0140$.

For the use of the 2AFC method, normalization (scale from 0 to 1) was adopted. Thus, the frequency values were normalized as follows:

$$w_a = \frac{w_a}{\sum_{a=3}^8 w_a} \cdot 0.7, \forall w_a = (0, 1) \quad (\text{SMP2.1})$$

$$\sum_{a=1}^8 w_a = 1 \quad (\text{SMP2.2})$$

where: w_a is the importance value of caste a in the ant colony; $w_1 = 0.29$, a value adopted considering that the queen has a vital role for the colony, who is solely responsible for reproduction; without the queen, the colony collapses [41,42]; $w_2 = 0.01$, a value adopted considering that the male has the sole function of fertilizing the queen during the nuptial flight, after which it dies and no longer participates in the colony [41,42].

The gradual microevolutionary change is the most parsimonious and logical inference for the ants [41]. Therefore, the importance values (w_a) for the young and old colonies in a climate change environment were calculated as follows:

- Step 1: new $w_a = w_a + 0.0100$, if w_a is impacted.
- Step 2: new previous neighbour

$$w_{a-1} = \begin{cases} w_{a-1} - 0.0050, & \text{if } a = 2, 3, \dots, 7 \\ w_{a-1} - 0.0100, & \text{if } a = 8 \end{cases}$$
- Step 3: new next neighbour

$$w_{a+1} = \begin{cases} w_{a+1} - 0.0100, & \text{if } a = 1 \\ w_{a+1} - 0.0050, & \text{if } a = 2, 3, \dots, 7 \end{cases}$$
- Step 4: new $w_a = w_a$, if w_a is not impacted.

S2-3. Calculation of the importance values (weights) of performance areas and Key Performance Indicators (KPI)

The importance values (weights) were obtained through consultations with operators and regulatory agents from hydropower plants, consisting of 3 hydropower plant operators and 3 regulatory agents. The consultation with the O.HPP was carried out according to the following activities:

- Presentation of the research, objectives, necessary data, and involved team.
- Provision of a questionnaire and request for responses to the following questions:
 (1) What is the importance value (weight) of the performance areas j ($j = 1, 2, \dots, n$), on a scale from 0 to 10, with 0 meaning "no importance" and 10 meaning "maximum importance"?
 (2) What are the first, second, and third most important KPIs (see Fig. SMP2.1) for performance area j ($j = 1, 2, \dots, n$)?

- Thanking for participation in providing data.

Mainly engineers working in the Brazilian electrical sector (hydropower plant operations, government regulatory institutions) were invited to participate in the questionnaire. A total of six responses were obtained, and we acknowledge the small sample size and the need for further efforts to expand it. The results from the questionnaires are summarized in Figure SMP2.4.

AD, j	OHPP1				OHPP2				OHPP3				OHPP4				OHPP5				OHPP6			
	V	1°	2°	3°	V	1°	2°	3°	V	1°	2°	3°	V	1°	2°	3°	V	1°	2°	3°	V	1°	2°	3°
1	7	2	1	3	10	1	3	2	10	1	2	3	7	1	3	2	6	1	3	2	10	1	3	2
2	6	2	4	3	8	1	3	4	10	6	2	1	8	2	6	3	8	2	1	6	10	2	1	6
3	8	3	4	5	7	3	2	1	8	3	5	2	2	1	4	2	10	1	4	5	10	1	4	5
4	8	4	4	2	9	1	2	9	9	3	2	1	3	4	8	9	10	2	1	4	10	2	1	4
5	8	6	6	9	9	2	5	8	7	1	8	9	2	1	4	6	10	1	8	5	10	1	8	5
6	8	1	12	4	10	7	15	17	9	15	1	3	8	7	5	3	10	16	13	8	10	16	13	8

NOTE: V is the importance value, ranging from 0 to 10; AD is the performance area, $j = 1, 2, \dots, n$; KPI is the key performance indicator, $i = 1, 2, \dots, m$; descriptions of i and j are available in Fig. SMP2.1.

Figure S2.4. Results of questionnaires applied to O.HPP.

The importance values (weights) of the performance areas and KPIs were normalized (scale from 0 to 1) as follows:

$$w_j = \frac{\sum_{j=1}^n V_j}{\sum_{H=1}^6 \sum_{j=1}^n V_{H,j}}, H = 1, 2, \dots, 6; j = 1, 2, \dots, n; \forall w_j = (0, 1) \quad (\text{SMP2.3})$$

$$\sum_{j=1}^n w_j = 1, j = 1, 2, \dots, n \quad (\text{SMP2.4})$$

$$w_{i,j} = \begin{cases} w_{i,j}^{II} + 0.05, \text{ se } w_{i,j}^I \\ w_{i,j}^{III} + 0.05, \text{ se } w_{i,j}^{II} \\ w_{i,j}^{IV} + 0.05, \text{ se } w_{i,j}^{III} \\ \frac{(1 - w_{i,j}^I - w_{i,j}^{II} - w_{i,j}^{III})}{m - 3}, \text{ otherwise} \end{cases}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (\text{SMP2.5})$$

$$\sum_{i=1}^m w_{i,j} = w_j, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (\text{SMP2.5})$$

where: V is the importance value according to the O.HPP, ranging from 0 to 10; H is the hydropower plant operator, $H = \text{O.HPP1}, \text{O.HPP2}, \dots, \text{O.HPP6}$; $w_{i,j}$ is the importance value (weight) of $\text{KPI}_{i,j}$; $w_{i,j}^I, w_{i,j}^{II}, w_{i,j}^{III}$, and $w_{i,j}^{IV}$ are the first, second, third, and fourth most important KPIs according to the O.HPP.

S2-4. Input data (performance in KPIs) and results

	Case 1
pR	0.7096
sj=1	0.6025 (8.99%)
y1,1 = 0.9	1.38% (15.39%)
y2,1 = 0.7	0.32% (3.55%)
y3,1 = 0.9	0.8% (8.9%)
sj=2	0.5969 (13.34%)
y1,2 = 0.9	1.43% (10.69%)
y2,2 = 0.3	0.78% (5.86%)
y3,2 = 0.1	0.09% (0.68%)
y4,2 = 0.2	0.11% (0.85%)
y5,2 = 1	0.56% (4.23%)
y6,2 = 0.3	0.17% (1.27%)
sj=3	0.5839 (10.15%)
y1,3 = 0.1	0.02% (0.2%)
y2,3 = 0.1	0.02% (0.2%)
y3,3 = 0.2	0.4% (3.95%)
y4,3 = 0.1	0.11% (1.09%)
y5,3 = 0.5	0.25% (2.5%)
y6,3 = 0.2	0.04% (0.41%)
y7,3 = 1	0.21% (2.04%)
y8,3 = 0.5	0.1% (1.02%)
sj=4	0.5827 (8.24%)
y1,4 = 0.2	0.01% (0.17%)
y2,4 = 0.2	0.16% (1.97%)
y3,4 = 0.1	0.01% (0.09%)
y4,4 = 63	0.31% (3.77%)
y5,4 = 0.4	0.03% (0.35%)
y6,4 = 0.6	0.04% (0.52%)
y7,4 = 0.1	0.01% (0.09%)
y8,4 = 0.1	0.01% (0.09%)
y9,4 = 0.8	0.25% (3.09%)
sj=5	0.5947 (8%)
y1,5 = 0.6	0.77% (9.68%)
y2,5 = 0.8	0.03% (0.4%)
y3,5 = 0.6	0.02% (0.3%)
y4,5 = 0.7	0.03% (0.35%)
y5,5 = 1.1	0.04% (0.54%)
y6,5 = 0.8	0.03% (0.4%)
y7,5 = 0.4	0.02% (0.2%)
y8,5 = 1	0.67% (8.32%)
y9,5 = 0.5	0.12% (1.55%)
y10,5 = 0.1	0% (0.05%)
sj=6	0.5965 (17.7%)
y1,6 = 0.8	0.33% (1.88%)
y2,6 = 0.1	0.04% (0.24%)
y3,6 = 0.2	0.17% (0.98%)
y4,6 = 93	0.42% (2.35%)
y5,6 = 0.1	0.04% (0.24%)
y6,6 = 0.1	0.04% (0.24%)
y7,6 = 0.1	0.31% (1.77%)
y8,6 = 0.8	0.33% (1.88%)
y9,6 = 0.5	0.21% (1.18%)
y10,6 = 0.1	0.04% (0.24%)
y11,6 = 2	0.83% (4.71%)
y12,6 = 0.1	0.04% (0.24%)
y13,6 = 0.4	0.71% (4.01%)
y14,6 = 0.3	0.12% (0.71%)
y15,6 = 0.3	0.12% (0.71%)
y16,6 = 0.1	0.04% (0.24%)
y17,6 = 0.5	0.21% (1.18%)
y18,6 = 0.2	0.08% (0.47%)

NOTE: The values of $y_{i,j}$ in the Case 1 columns indicate their percentage contribution to p_R and s_j ; for $y_{i,j}$ the percentage value without parentheses is the contribution to p_R , the value in parentheses is the contribution to s_j ; for s_j the value in parentheses is the contribution to p_R

Figure S2.5. Results of the 2AFC model, Case 1

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