Risk
Univ. Grenoble Alpes

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Physics-Informed Deterioration Modeling and Maintenance Optimization Using Stochastic Petri Nets: Application to Torrent Protection Structures

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INRAE

MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE ET SOLIDAIRE
Liberté
Égalité
Fraternité

OUTLINE

OUTLINE

BACKGROUND

Torrential Phenomena

Characteristics

Magnitude
Intensity
Frequency
Effect

Flood in Malnant torrent (FRANCE)

Debris flow © P.Zufferey

Risk imposed to

Torrential watershed

Reception area

Flow channel

Downstream alluvial fan

Manival torrent (FRANCE)

BACKGROUND

Natural Risk Assessment

Risk = **Hazard** X **Vulnerability** X **Exposure**

(IPCC)

Hazard: **Frequency** (likelihood) X **Intensity** (e.g. discharge)

Vulnerability: **Damages** (potential consequences)

Exposure: **Elements at risk** (e.g. people) X **Value** (e.g. cost)

Destruction

Deposition

Erosion/Scouring

BACKGROUND

Interdependent protection system

Series of check dams

Pontamafrey torrent (France)

Retention dam

Claret torrent (France)

Dykes/Levees

Saint Bernart torrent (France)

Torrential watershed

Reception area

Flow channel

Downstream alluvial fan

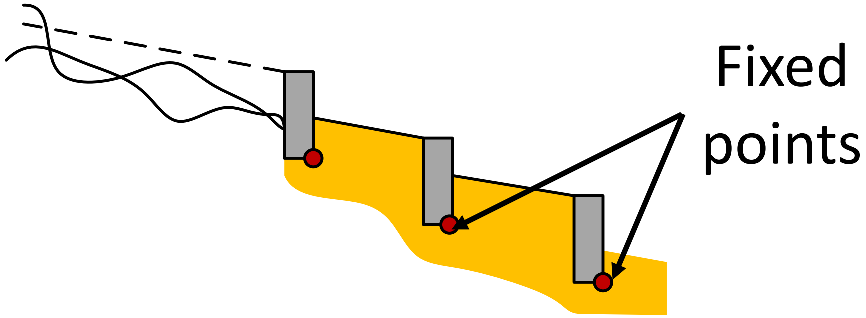
Structures acting on causes

Structures acting on consequences

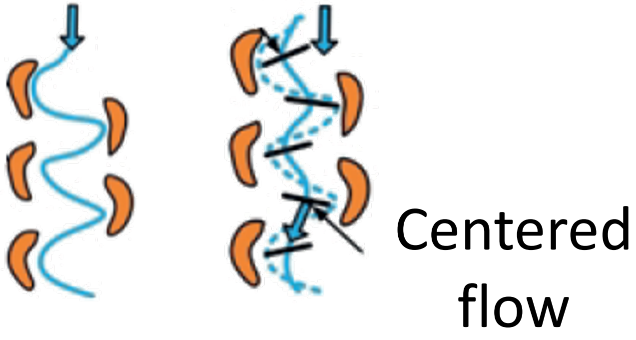
Manival torrent (FRANCE)

BACKGROUND

Longitudinal profile

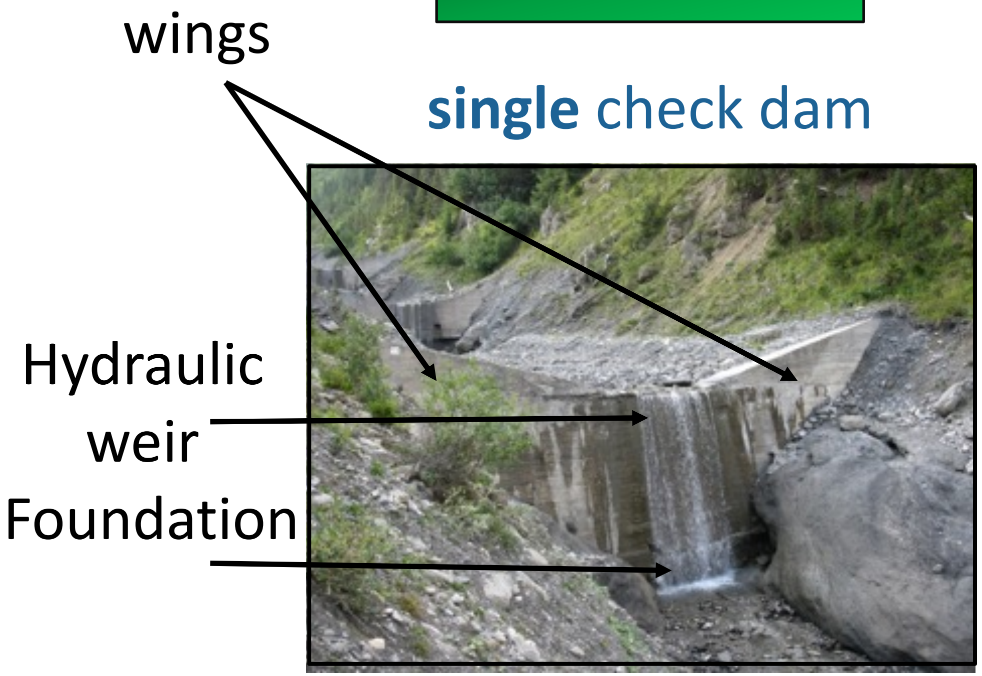


Top view



Torrent check dams

COMPONENT	SYSTEM	FUNCTIONS
single check dam	**series** of check dams	



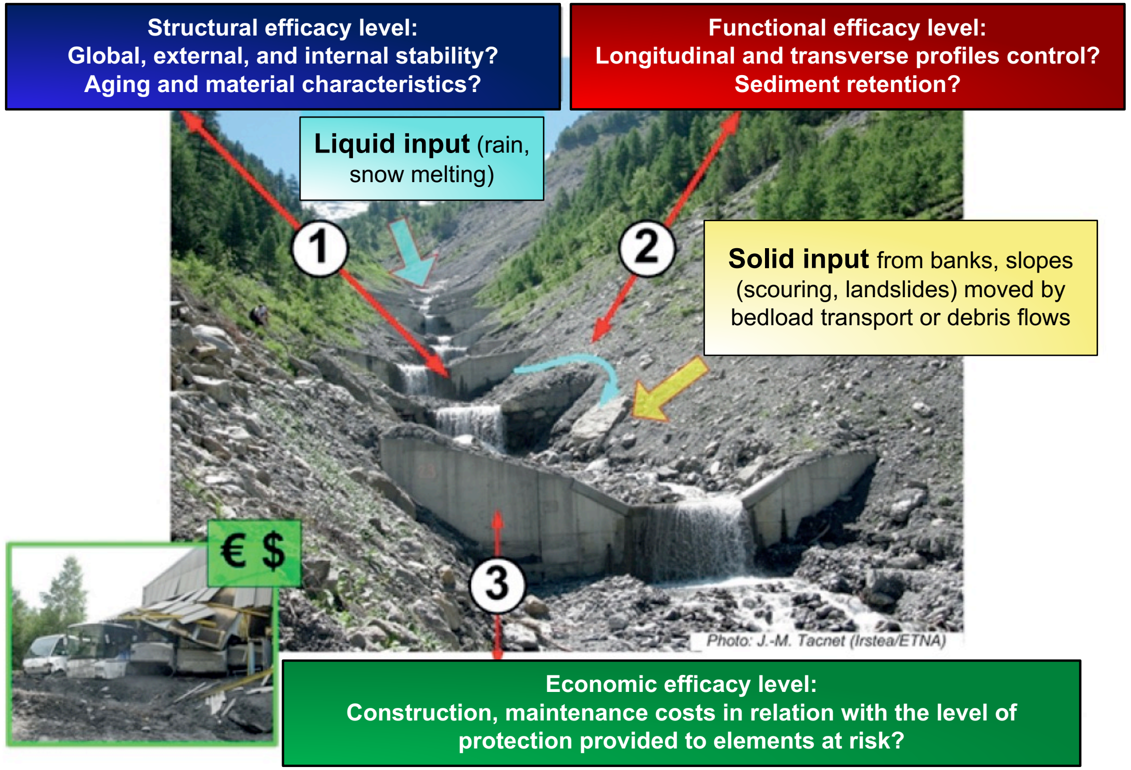
- Slope reduction
- Bed stabilization
- Sediment transport regulation
- Flow centering

OUTLINE

SCIENTIFIC & TECHNICAL CHALLENGES

Efficacy assessment

Are these structures functionally and/or structurally effective?



(Source J.-M. Tacnet)

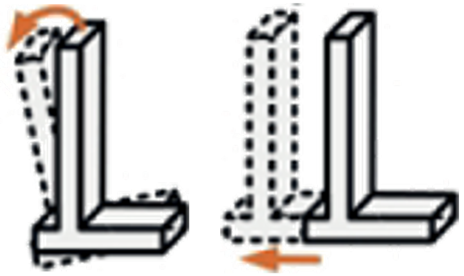
Check dams' failures modes

Structural

Loss in **internal** and **external** stability

cracks, corrosion, ...

overturning, sliding, ...

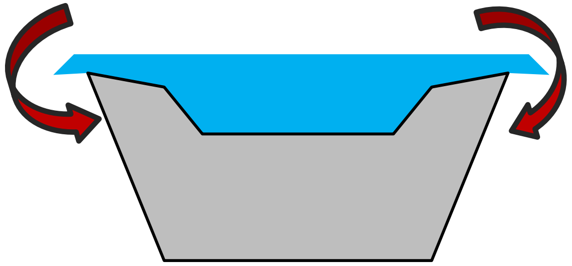


Functional

Fail to **fulfill** expected **functions**

scouring

Lateral bypass

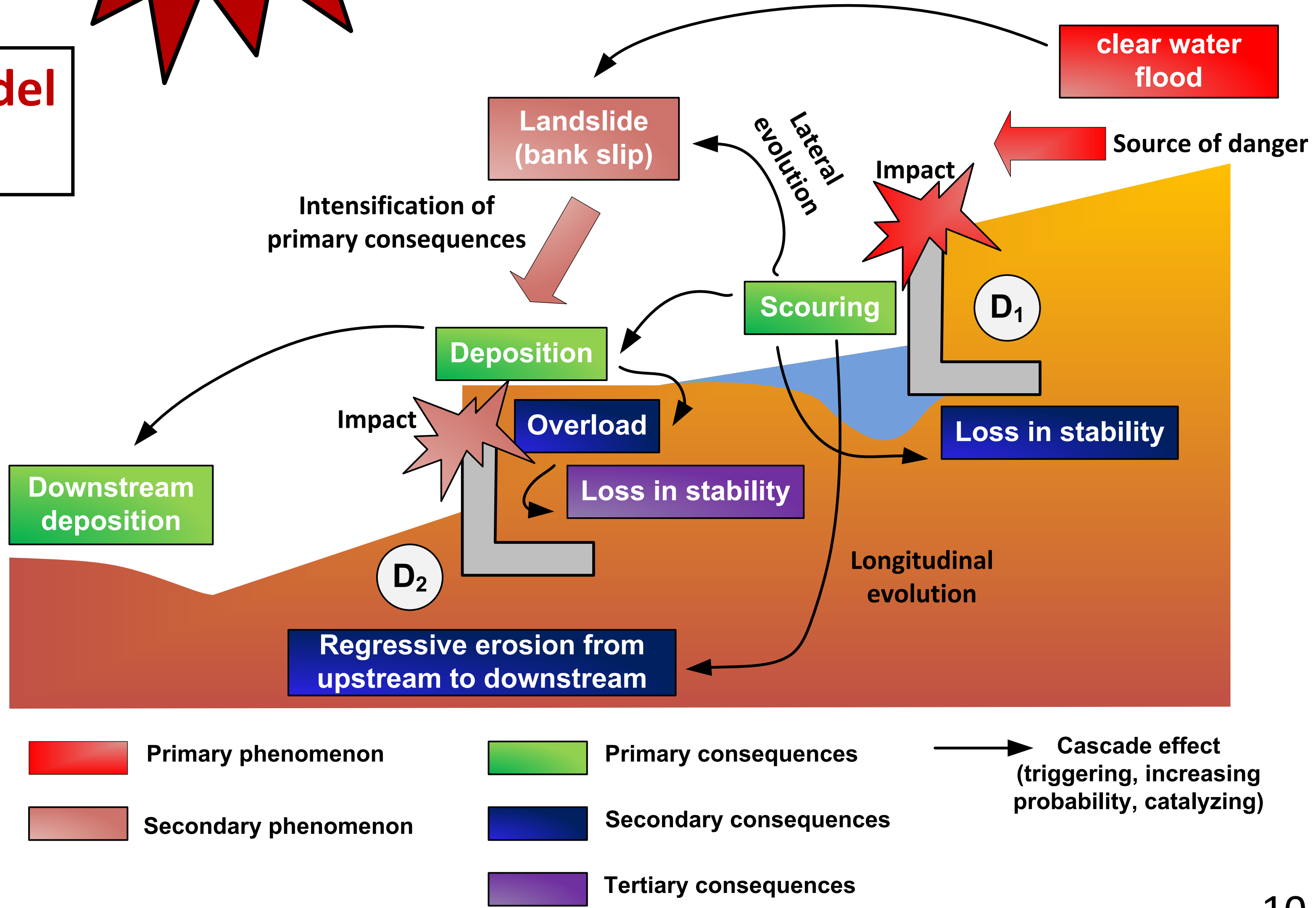


SCIENTIFIC & TECHNICAL CHALLENGES

Cascade effect

How to figure out and model existing dependencies?

Multi-component protection system



Cascading effect due to:

1. Interactions between hazards
2. Dependencies between failures modes
3. Bi-directional dependencies between structures

SCIENTIFIC & TECHNICAL CHALLENGES

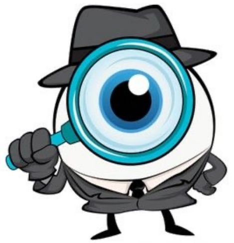
Budgetary constraints

Cost-Benefit analysis

Which maintenance strategy is the most cost-effective?

Is it worth it to maintain these structures in comparison to the provided level of protection?

Interventions



- **Inspection**
  Monitor, diagnose,…

  When? How often?

- **Maintenance**
  Preventive (repair), corrective (re-construct), …

  When? What? How much?

Downstream risk level

Maintenance efficiency

Residual risk?

SCIENTIFIC & TECHNICAL CHALLENGES

How to asses the effect of information imperfection on decisions?

Uncertainty analysis

Collected data

Assumptions

Numerical models

Expert assessment

Information

- Nature
  - Objective
  - Subjective
- Content
  - Quantitative
  - Qualitative

Imperfection

- Uncertainty
  - Random or Epistemic
- Inconsistency
  - Conflict
- Imprecision
  - Vague
- Incompleteness
  - Insufficiency

OUTLINE

1 Background

2 Scientific and Technical Challenges

3 Research Novelty & Contributions

4 Developed Modeling Approach

5 Performance Analysis & Case Studies

6 Conclusions and Perspectives

RESEARCH NOVELTY

- ✓ **Dynamic and long term efficacy assessment**

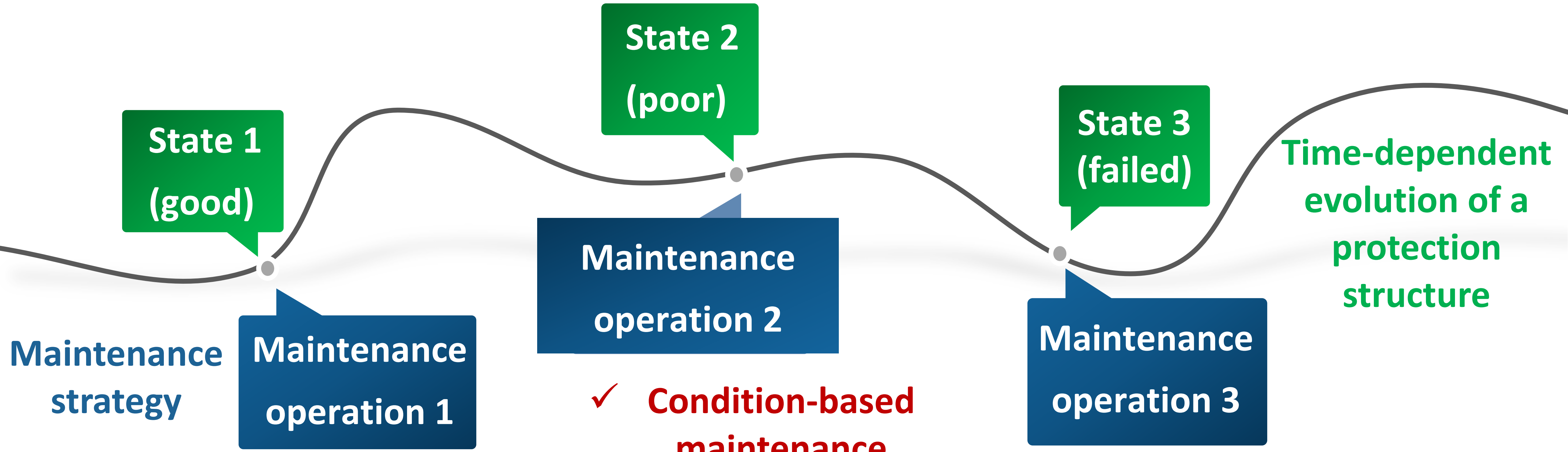
SOTA in the context of torrent protection structures

- ❑ **Static assessment** of protection structures **efficacy**

  Use of basic or static reliability techniques (e.g. **FMEA**, **FTA**, and **ETA**)
- ❑ **Maintenance decisions** based on **static vision**

  Use of classical decision-making techniques (e.g. **CBA**, **MCDM**)

(Carladous, 2017)



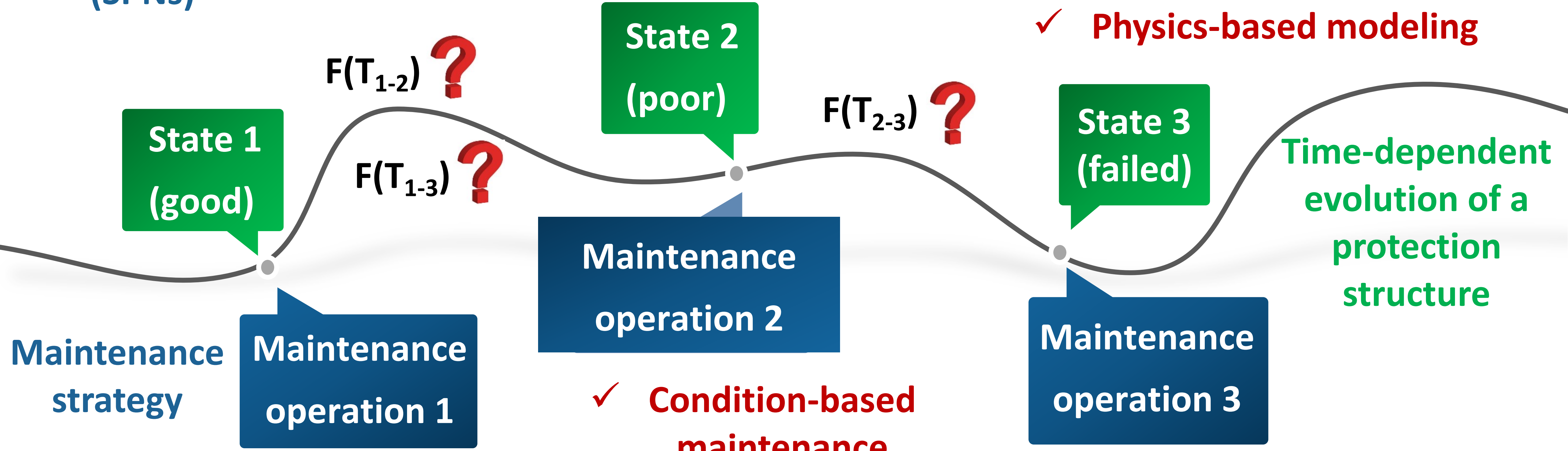
✓ **Condition-based maintenance**

RESEARCH NOVELTY

- ✓ **Dynamic and long term efficacy assessment using stochastic Petri nets (SPNs)**

SOTA in the context of system's reliability analysis

- ❑ **Transition laws** between states are **estimated** by the:
  - Use of **exponential distribution** for simplicity (constant failure rate)
  - Use of **real data** in order to fit a suitable probability distribution
- ❑ **Applications** in civil engineering context:
  - Bridges: Weibull ***(Le and Andrews, 2016) (Le et al., 2017)***
  - Railway network: Gamma ***(Shang, 2015),*** Weibull ***(Litherland, 2019)***



- ✓ **Physics-based modeling**
- ✓ **Condition-based maintenance**

RESEARCH NOVELTY

Civil engineering

- ❑ Coping with **interactions** between **failure modes**

  How can **local scouring** trigger failure by **external stability**?

Multi-component protection system

- ❑ Coping with complex **interacting systems/structures**

  How does the **failure** of **one component** affects the **behavior** of **other components**?

Protection system's maintenance decision-making

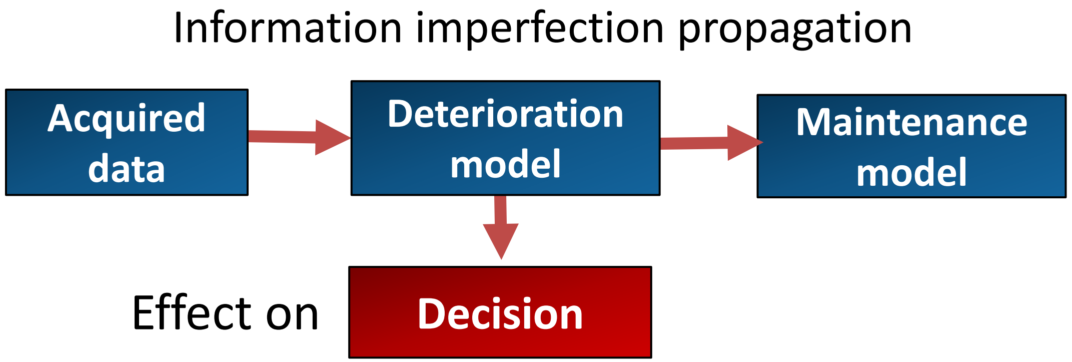
- ❑ Coping with **information imperfection**

  How does **information imperfection** affects decisions?

✓ **Cascade effect analysis**

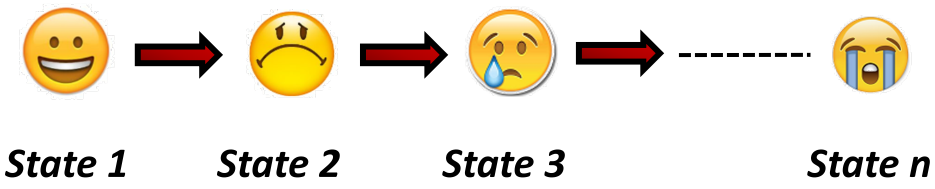
✓ **Integrating information imperfection in decision models**

CONTRIBUTIONS



1

Proposing a **physics-based model** that models the **time-dependent state-evolution** of **protection structures** when being **subjected to torrential phenomena** considering **cascade effect**



2

Developing a **stochastic deterioration and maintenance model** using **SPNs** in order to **support maintenance decision-making** of protection structures considering **economic aspects**

3

Analyzing the **performance**/behavior of two types of protection structures (**check dams** and **retention dams**) using the developed modeling approach

4

Propagating uncertainty within the deterioration and maintenance model and performing a **sensitivity analysis**

OUTLINE

MODELING APPROACH

General approach

(can be applied to any deteriorating system)

Risk scenario definition

- Data acquirement
- Hazard scenarios
- Consequences

Physics-based model

- Dynamic behavior of the system
- Cascade effect
- Transition laws

Decision-aiding model

- Stochastic deterioration & maintenance modeling
- Maintenance optimization (cost-effective)

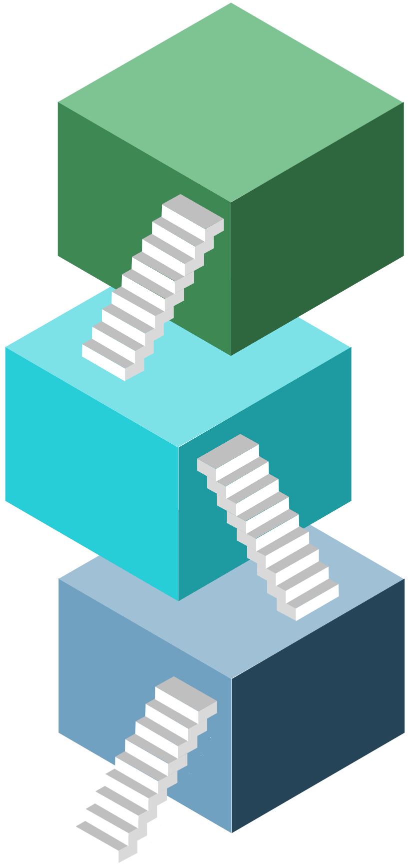
MODELING APPROACH

Risk Scenario Definition

Check dams subjected to clear water floods

STAGE 3

Cascade effect analysis between the torrent's **bed** behavior, **scouring** variation, and check dam's **stability** level evolution



STAGE 2

Generation of **clear water flood** events scenarios

STAGE 1

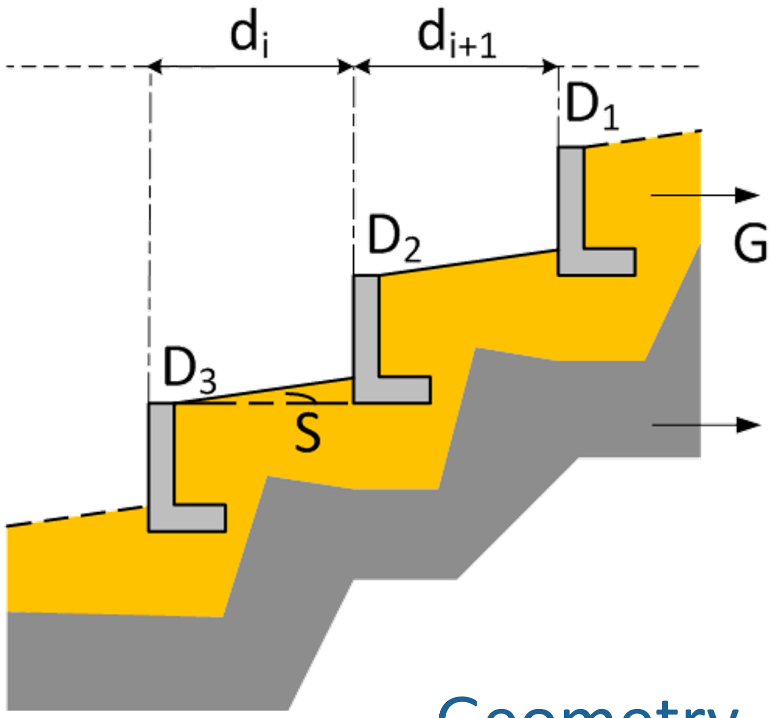
Data collection

MODELING APPROACH

Risk Scenario Definition

STAGE 1

Longitudinal profile

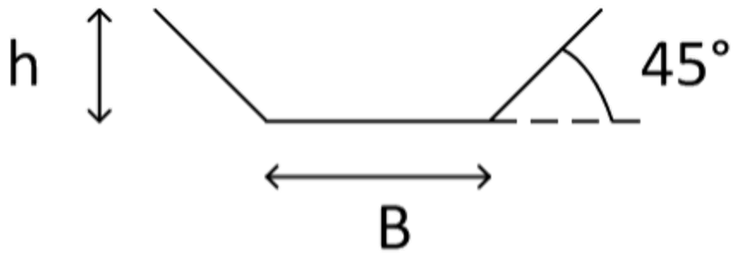


Erodible layer:
Grain size distribution
D_{30}, D_{50}, D_{90}, etc...

Substratum

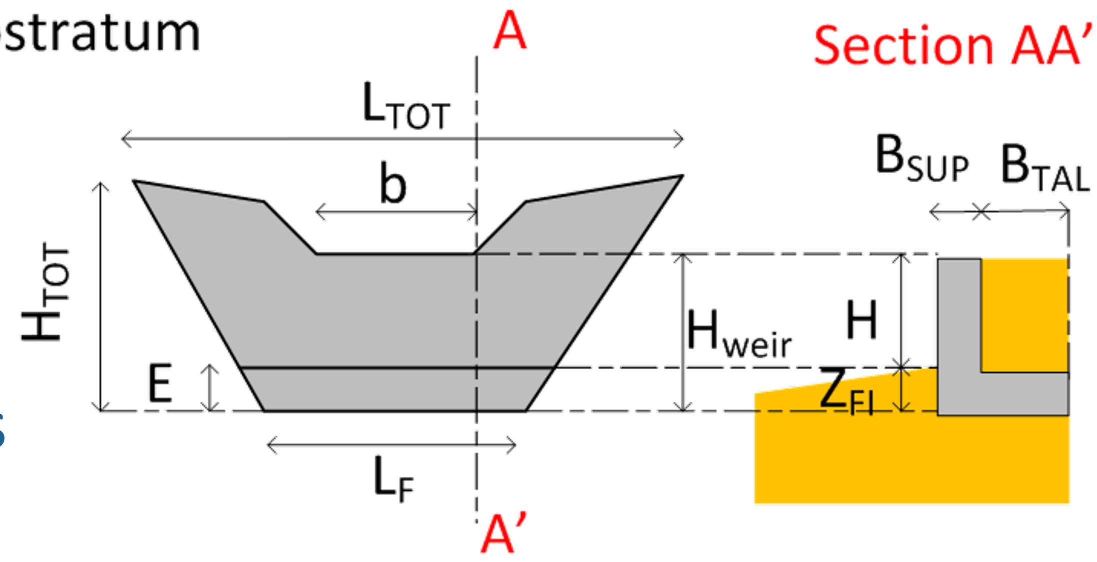
Transverse profile

Trapezoidal
cross-section



Channel width

Geometry,
dimensions of dams



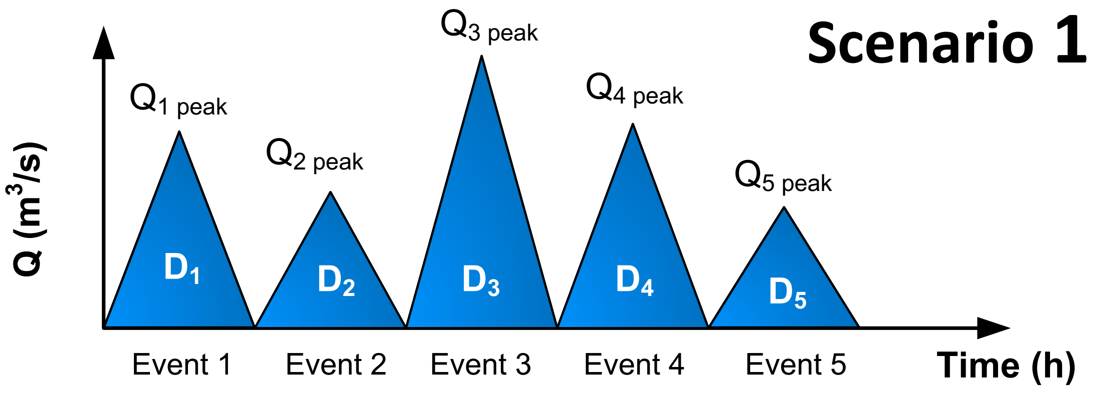
Geotechnical
data

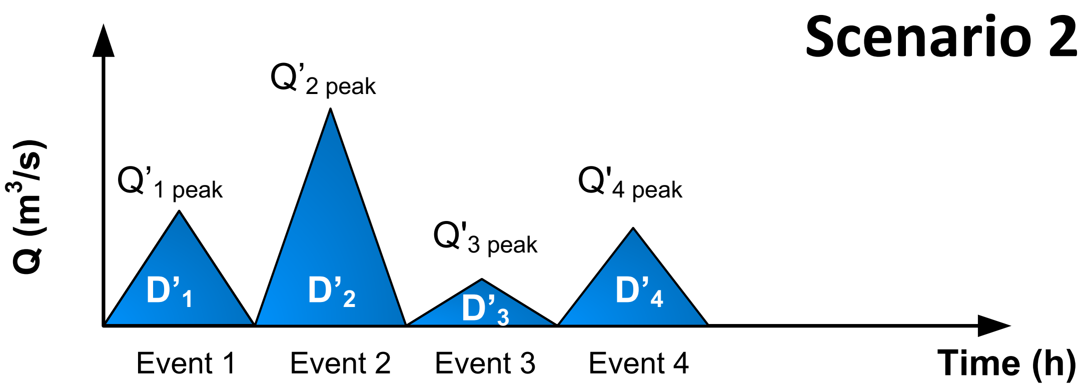
MODELING APPROACH

Risk Scenario Definition

STAGE 2

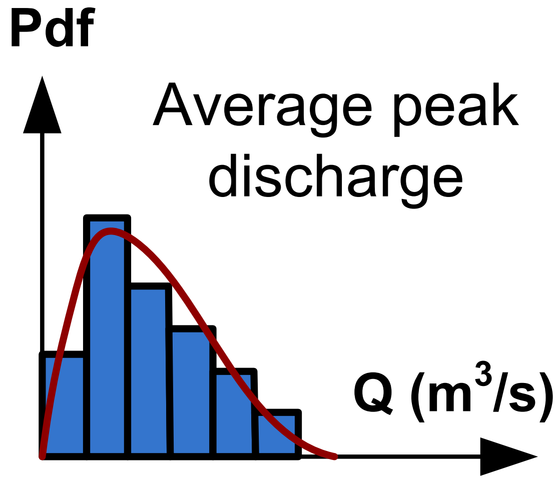
Generation of n flood series scenarios

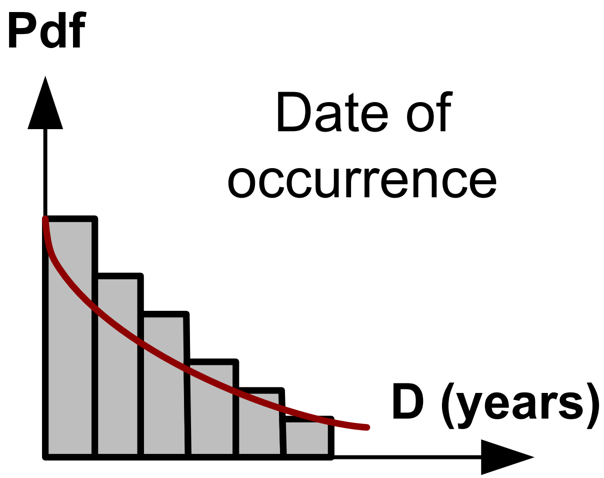




- - - - - - - - - - - - - - - - - - **Scenario n**

Randomness



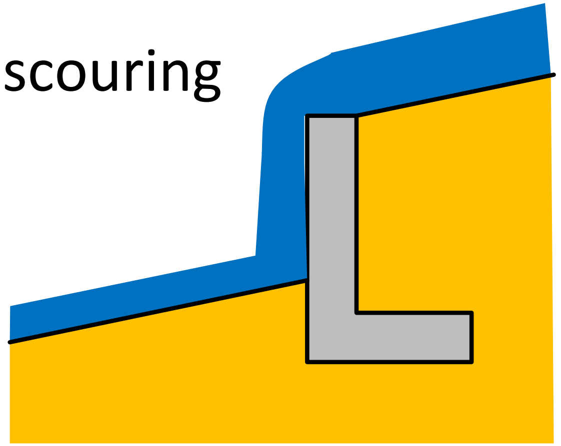


MODELING APPROACH

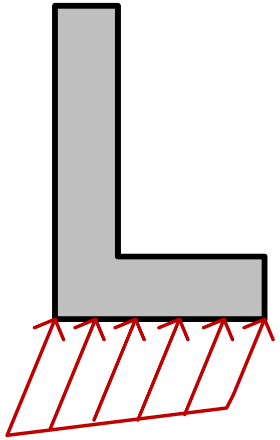
Risk Scenario Definition

STAGE 3

Before scouring

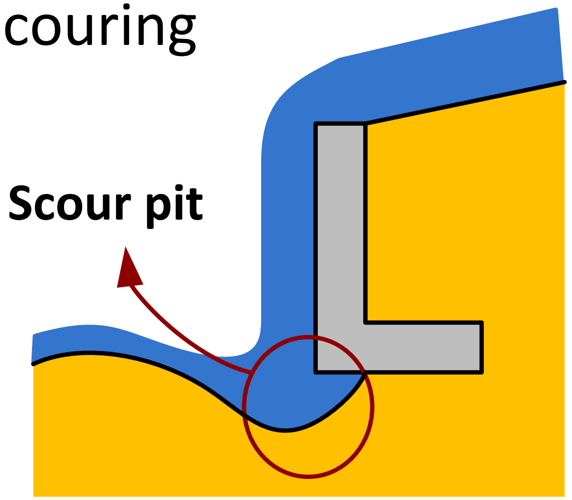


Stress distribution

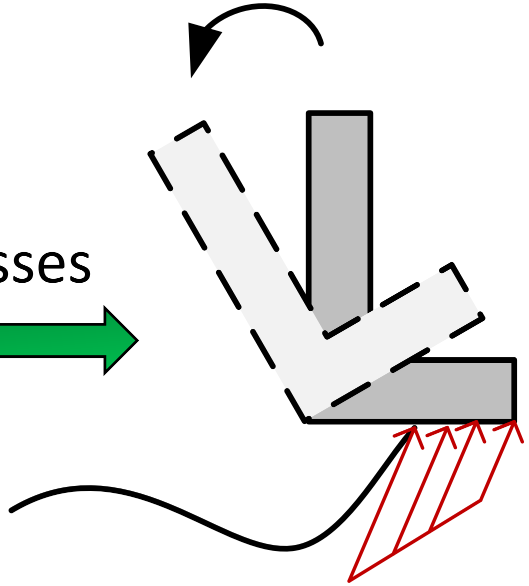


External stability conditions are fulfilled

After scouring



Redistribution of stresses



Loss in external stability: risk of collapse (e.g. by overturning, soil rupture, etc.)

MODELING APPROACH

Physics-based Model
Considering cascade effects

STAGE 2
Check dam's **states** definition
Transition probability laws estimation

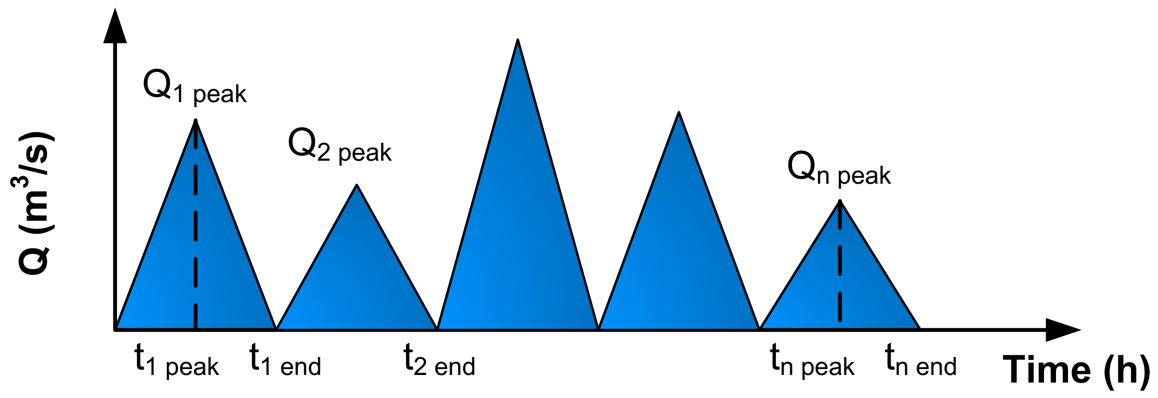
STAGE 1
Bed evolution
Scouring calculation
External **stability** justification
Global **stability index** definition

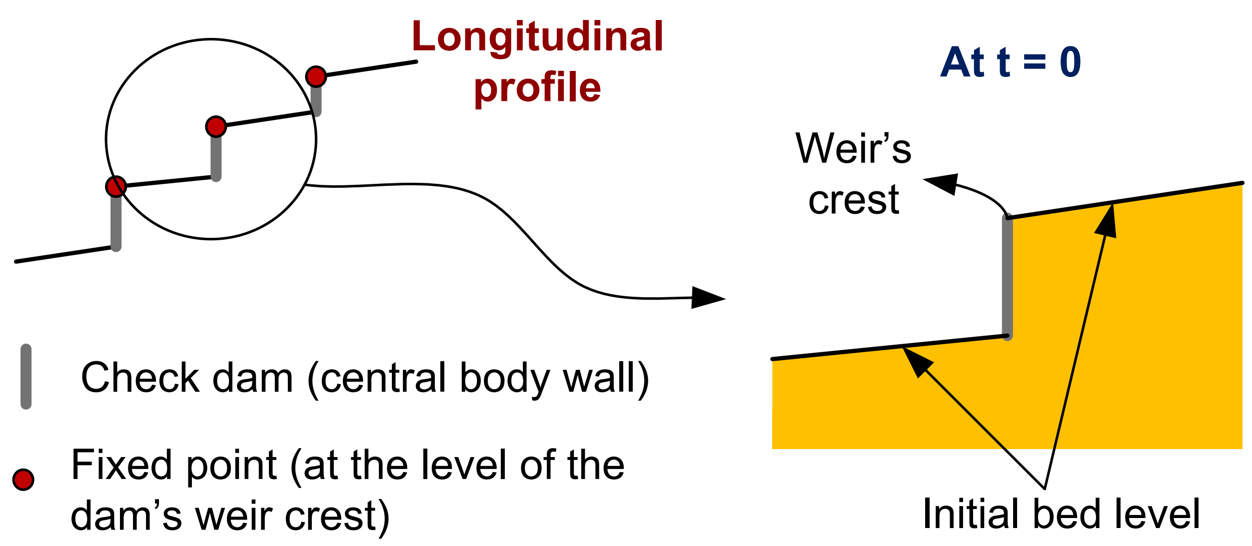
MODELING APPROACH

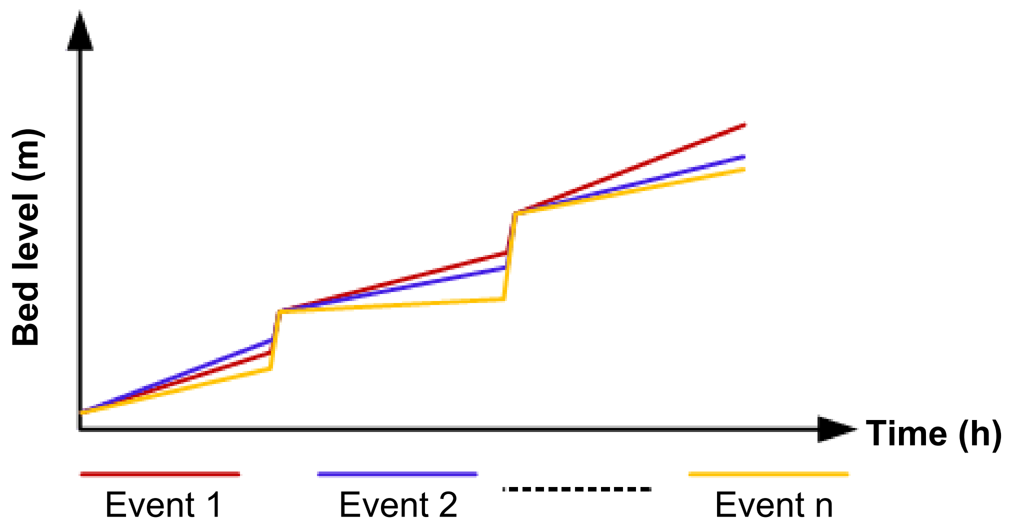
Physics-based Model

STAGE 1

1 Time-dependent **bed evolution** modeling via **LOGICHAR** ***(Laigle, 2018)***







MODELING APPROACH

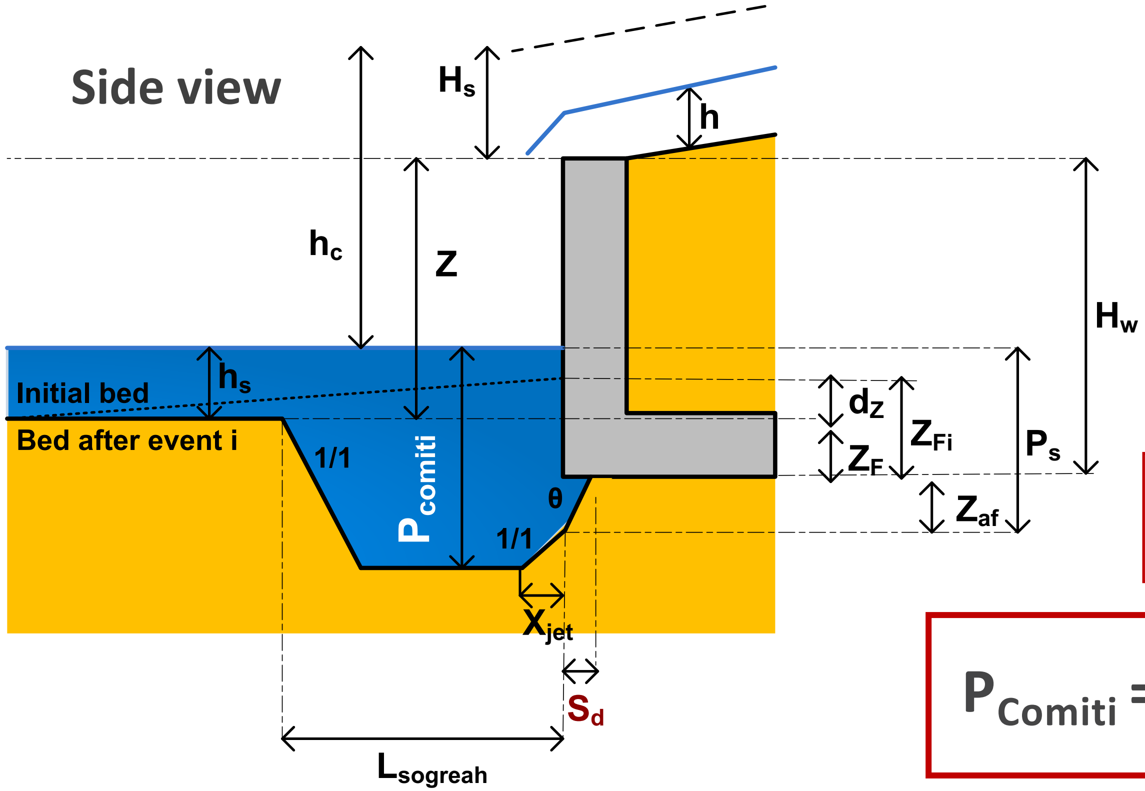
Physics-based Model

STAGE 1

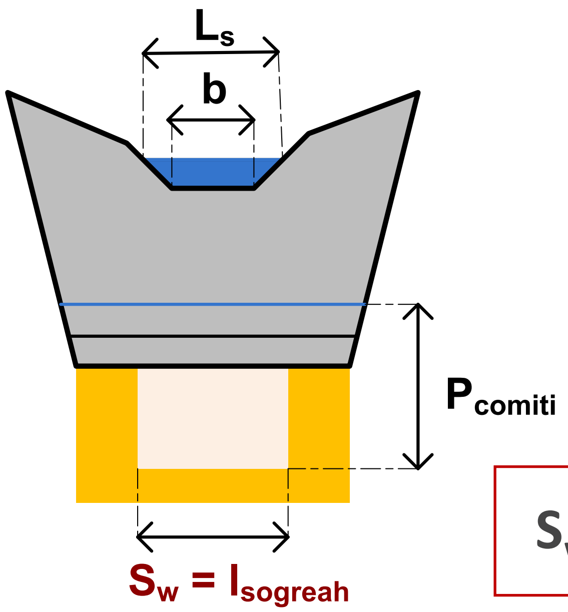
2 Global and local **scouring estimation**

Combination of ***Sogreah (1989)*** *and* ***Comiti et al. (2013)*** methods

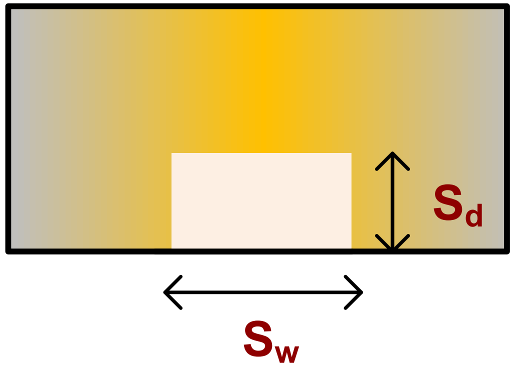
Side view



Front view



Bottom view



$$S_w = l_{Sogreah} = P_{Sogreah} * R'$$

$$S_d = Z_{af} = f(P_{Sogreah}, Z_F, h_s, X_{jet})$$

$$P_{Sogreah} = P_{Comiti} * R$$

$$P_{Comiti} = 2Z(H_s/Z)^{0.59} * (b/B)^{2.34} * (\Delta D_{90}/Z)^{-0.09} + h_s$$

MODELING APPROACH

Physics-based Model

STAGE 1

4 Global stability indicator definition

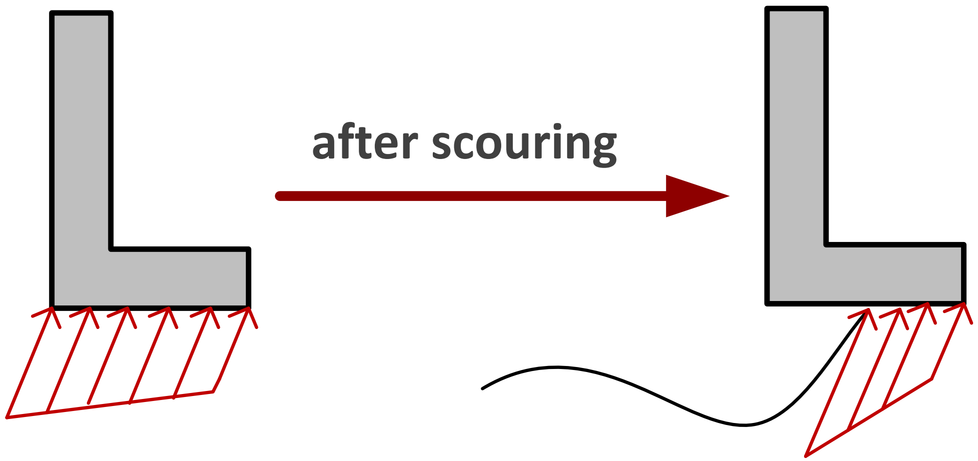
$$S_g = \left(S_{BC}{}^{\alpha} * S_{OT}{}^{\beta} * S_{SL}{}^{\gamma}\right)^{1/(\alpha+\beta+\lambda)}$$

3 External stability justification

(Deymier et al., 1995) (Groupe de travail, 1993)

Exceedance of bearing capacity

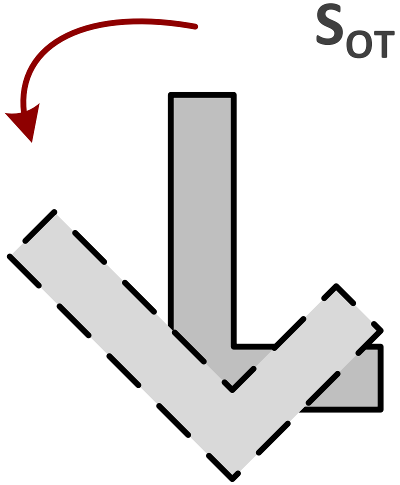
S_{BC}



$$S_{BC} = \frac{\sigma_{adm} - q'_r ef}{\sigma_{adm}}$$

Stability against overturning

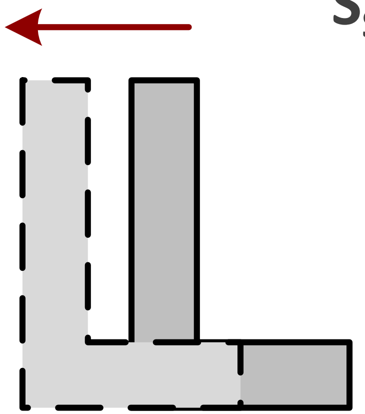
S_{OT}



$$S_{OT} = \frac{M_S - M_O}{M_S}$$

Stability against sliding

S_{SL}



$$S_{SL} = \frac{R_{SL} - R_H}{R_{SL}}$$

MODELING APPROACH

Physics-based Model

STAGE 2

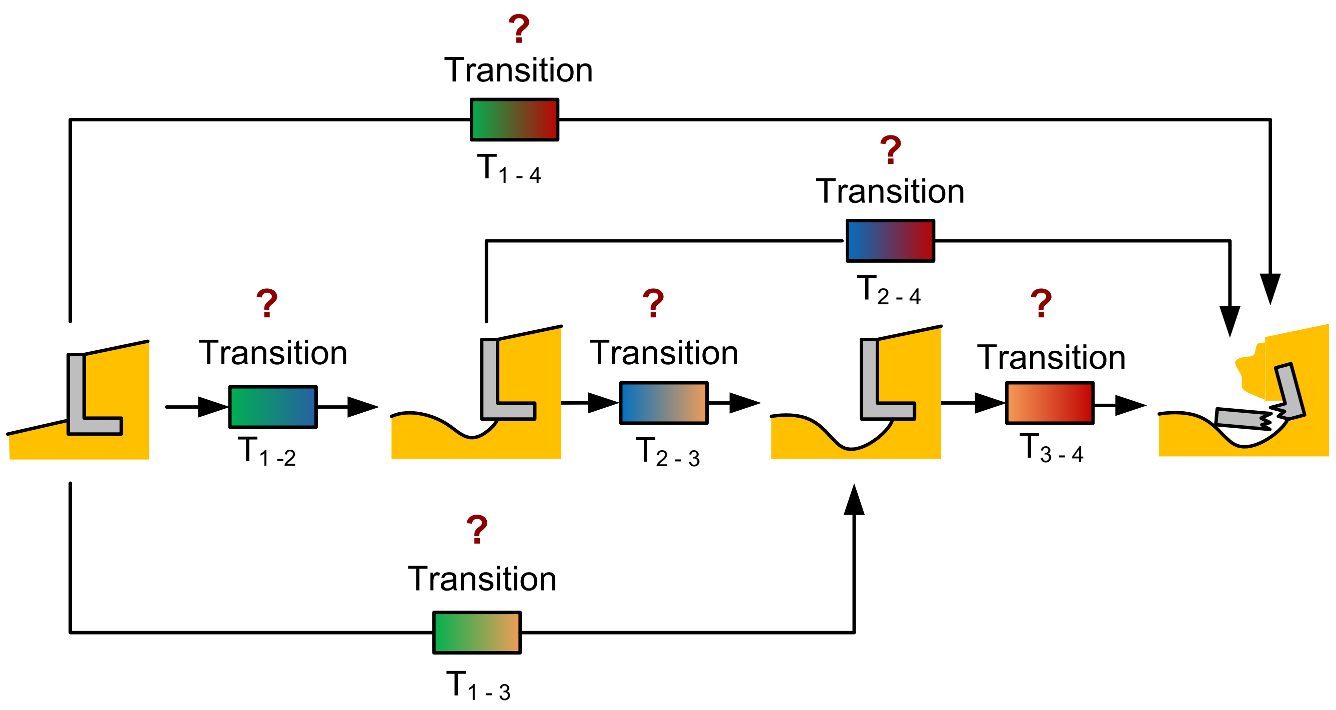
1 Check dam's **states definition**

State 1
New – good condition

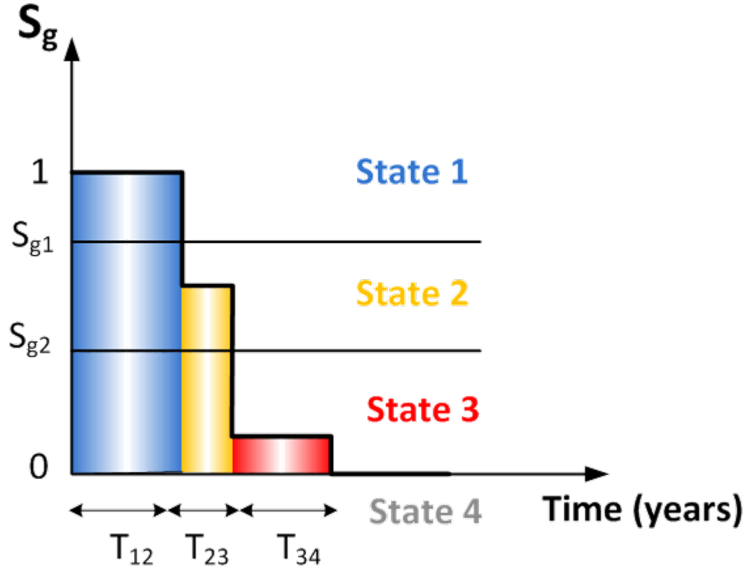
State 2
Poor condition

State 3
Very poor condition

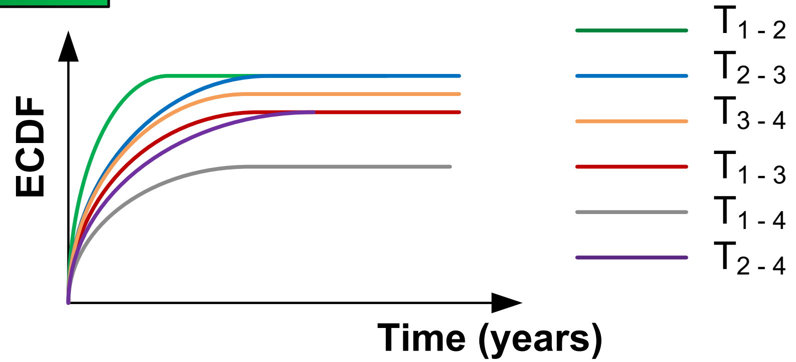
State 4
Failed condition



2 Time-dependent evolution of S_g



3 Transition laws estimation



MODELING APPROACH

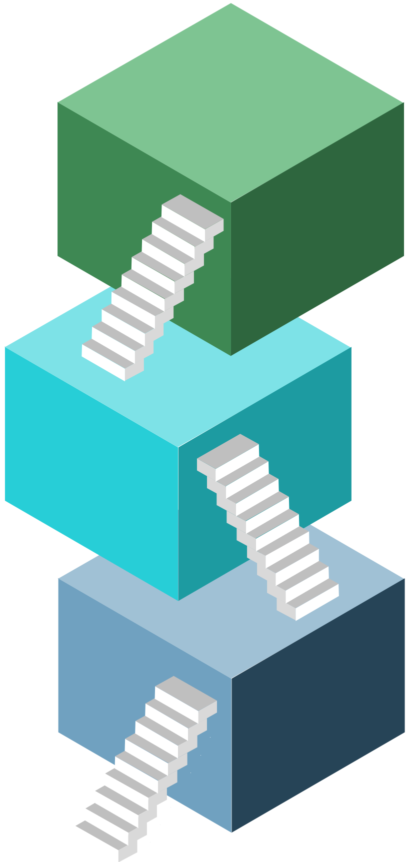
Stochastic Deterioration & Maintenance Model

Stochastic Petri Net (SPN) Model

STAGE 3

Apply Monte-Carlo simulation

Compare maintenance strategies



STAGE 2

Define different maintenance strategies

STAGE 1

Construct the SPN model

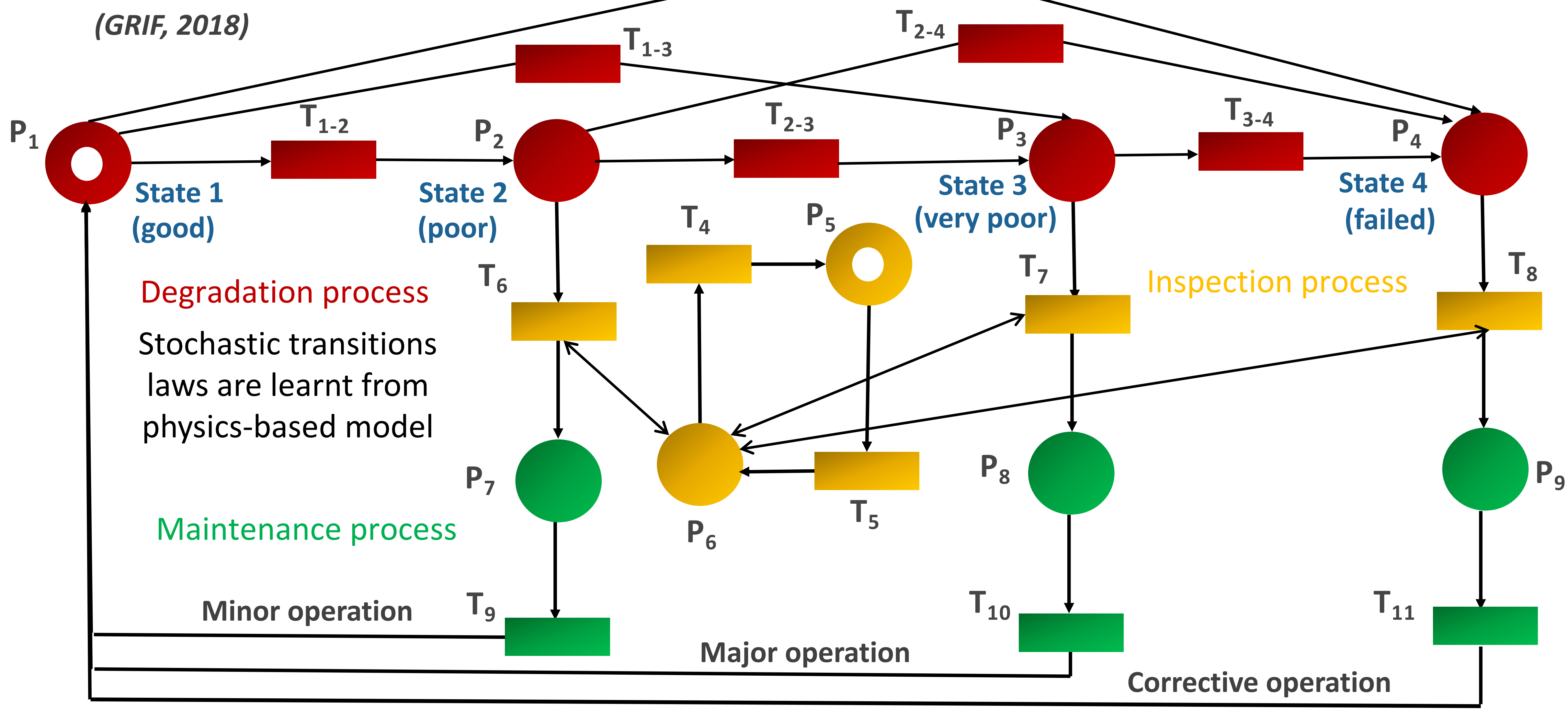
MODELING APPROACH

Stochastic Deterioration and Maintenance Model

STAGE 1

State-evolution of a **deteriorating system** subjected to **maintenance policy**

(GRIF, 2018)



MODELING APPROACH

Stochastic Deterioration and Maintenance Model

STAGE 2

Maintenance strategy 1:
All maintenance operations are **allowed**

Maintenance strategy 2:
Minor operations are **inhibited**

Maintenance strategy 3:
Major operations are **inhibited**

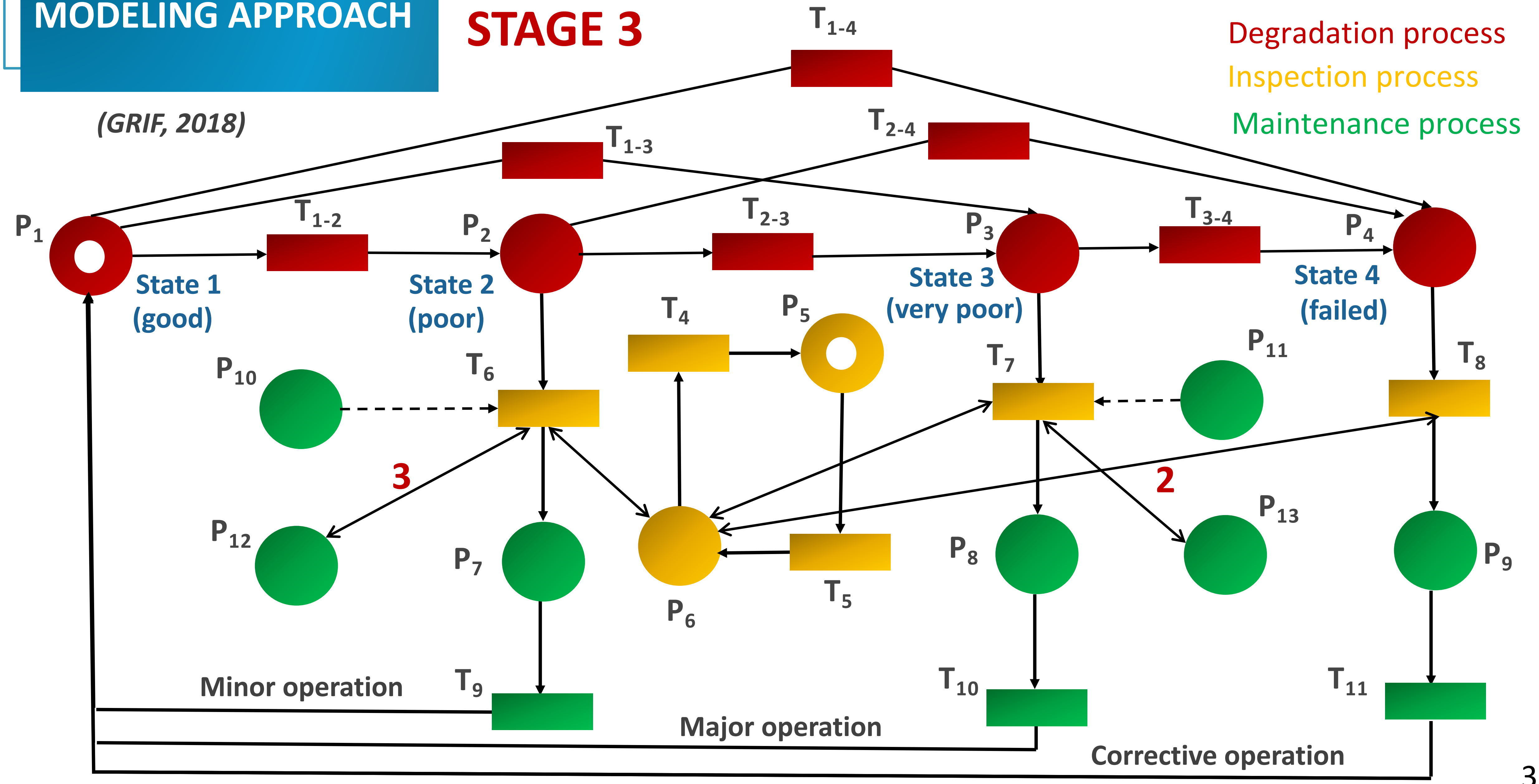
Maintenance strategy 4:
Only corrective operations are **allowed**

Condition for the case of check dams:
Three minor operations and **two major** operations are allowed **prior** to **corrective maintenance** operation

Stochastic Deterioration and Maintenance Model

STAGE 3

(GRIF, 2018)



OUTLINE

PERFORMANCE ANALYSIS

Analysis of protection structures' performance
(using the proposed modeling approach)

Performance analysis of protection structures

- Deterioration
- Maintenance

Uncertainty analysis

- Uncertainty propagation
- Sensitivity analysis

Analysis of bi-directional dependencies

- Multi-component system
- Components' interactions

CASE STUDIES

Development and Evaluation of a Complete Deterioration and Maintenance Model on Torrent Protection Structures

Case study 1
Single check dam

Case study 2
Multi-components system of check dams

Case study 3
Retention system

CASE STUDY 1

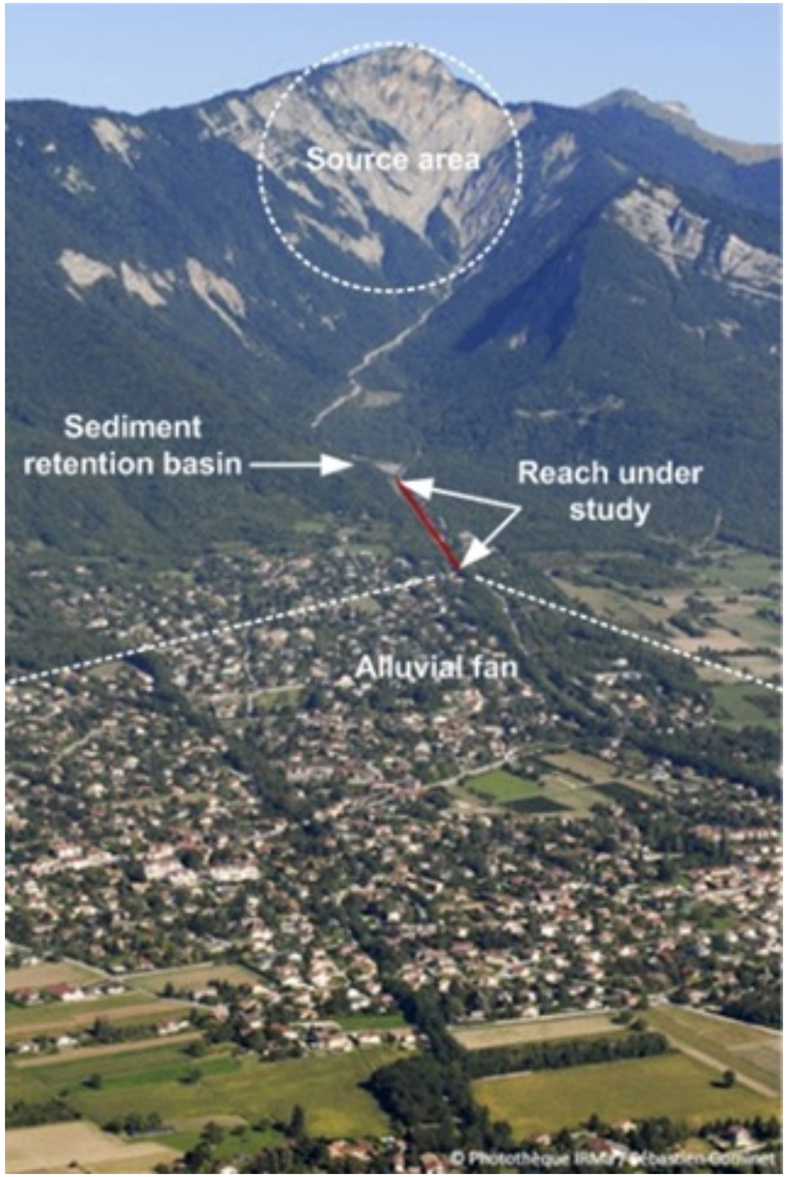
Check Dam Subjected to Clear Water Floods in the Manival Torrent

(Chahrour et al. RESS 2021)

1 Risk scenario definition

- **Data collection (ONF – RTM database)**
  - Longitudinal & transverse profiles
  - Grain size distribution
  - Geotechnical data
  - Check dams' dimensions

- **Flood scenarios**
  - Random generation of 50 scenarios
  - **Clear water flood** events
  - Floods with **return period** of **10 years**
  - **Time period** considered: **100 years**



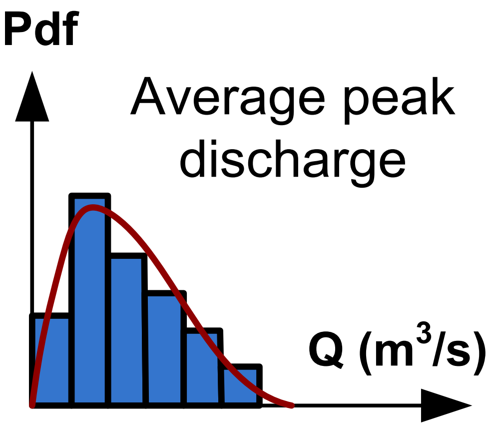
Manival torrent (FRANCE)

CASE STUDY 1

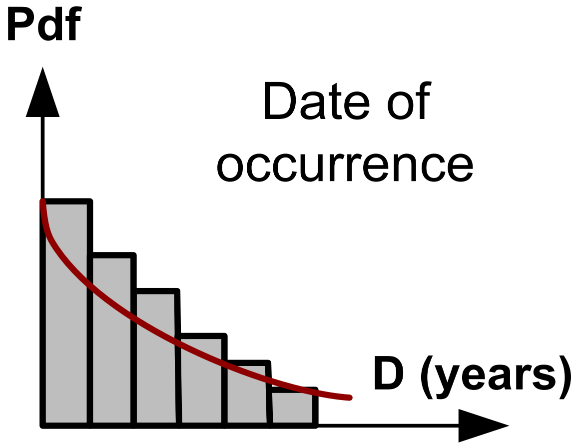
Risk scenario definition

(Chahrour et al. RESS 2021)

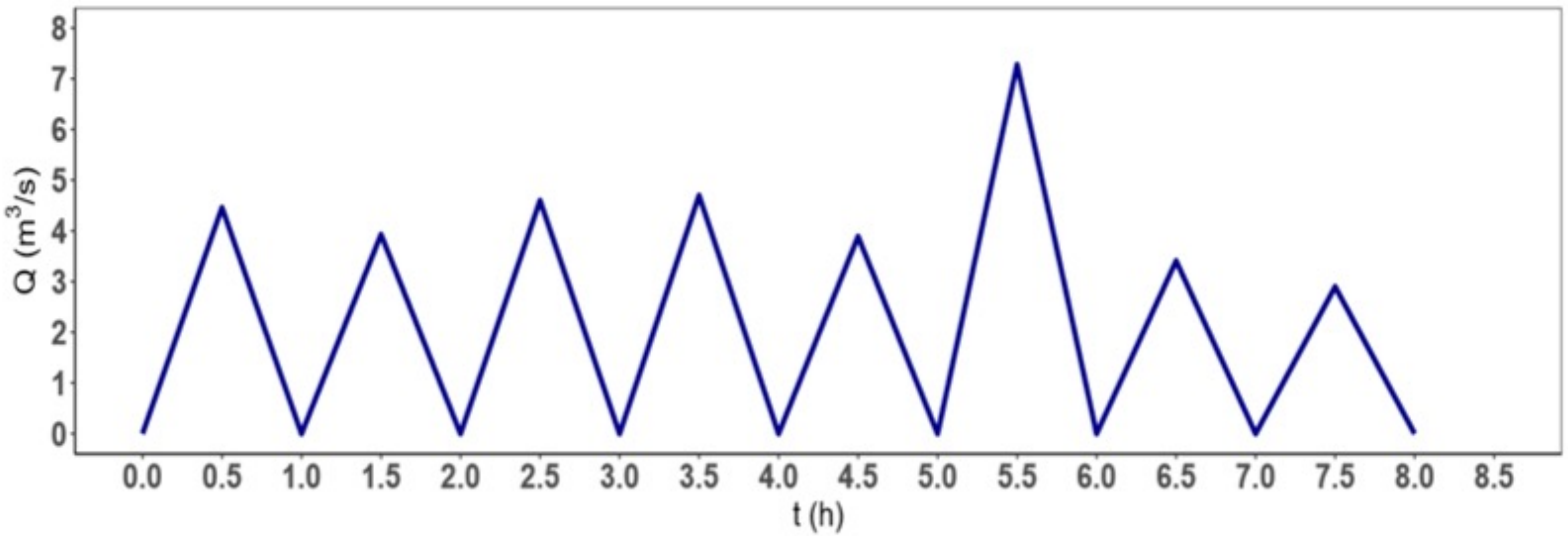
Q_{avg} (T = 10 years) = 5 m3/s
~ ***Gamma law*** (α = 5, β = 1)



T = 10 years
~ ***Poisson law*** (λ = 1/10)



Hydrograph showing a series of flood events – scenario 1.



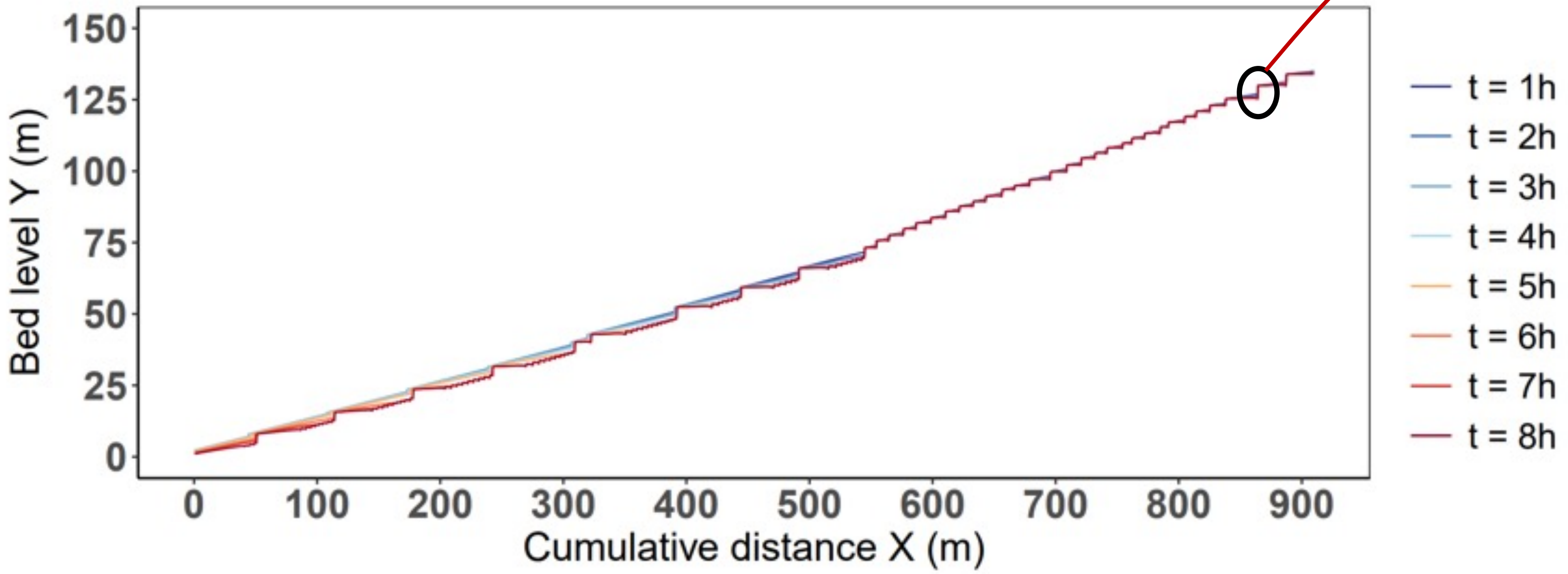
CASE STUDY 1

Performance Analysis using the Physics-based model

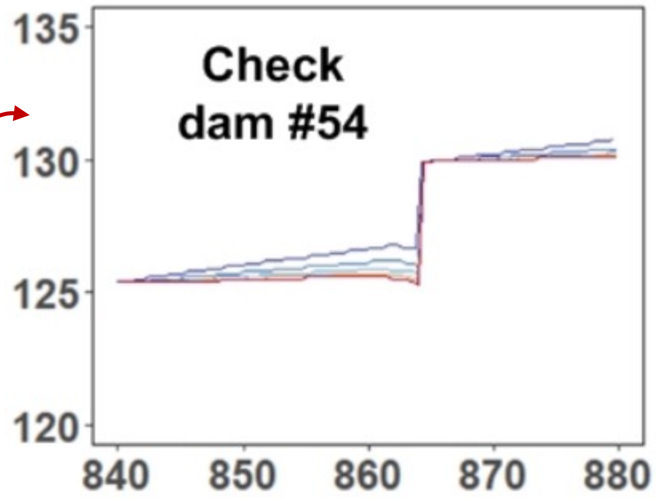
(Chahrour et al. RESS 2021)

LOGICHAR simulations (e.g. scenario 1)

Reach down stream retention dam (39 check dams)



Variation in bed level along the entire studied reach.



Variation in bed level upstream and downstream check dam #54.

CASE STUDY 1

Performance Analysis using the Physics-based model

(Chahrour et al. RESS 2021)

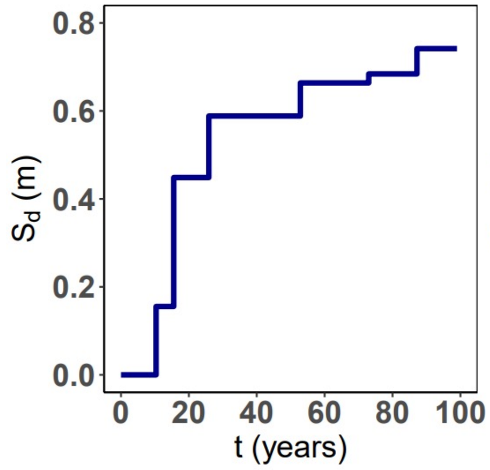
Time-dependent evolution of degradation indicators(e.g. scenario 1)

Check dam #54

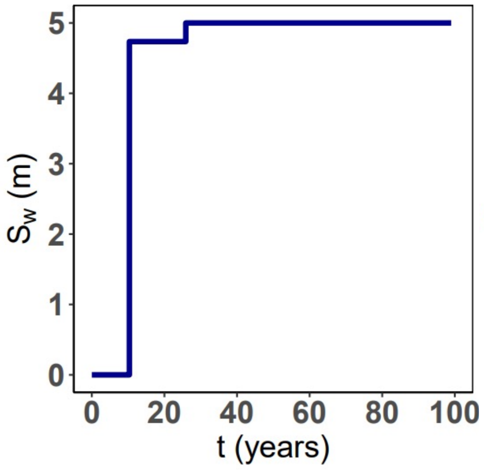
Scouring indicators

Stability indicators

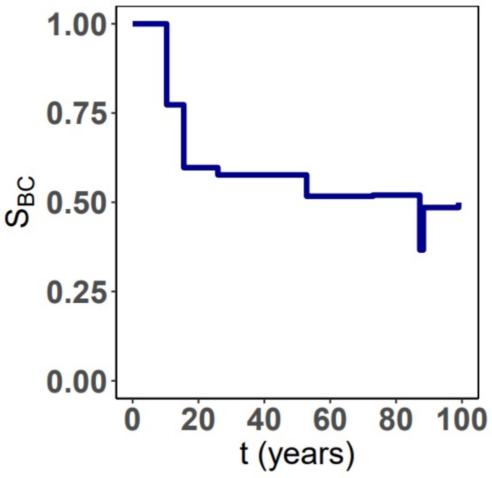
S_d **S_w** **S_{BC}** **S_{OT}** **S_{SL}**



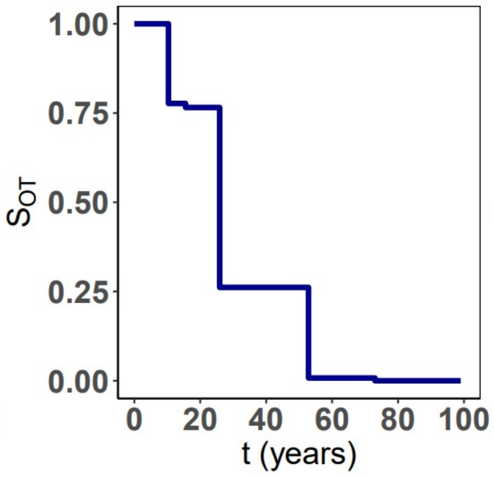
Local scouring depth



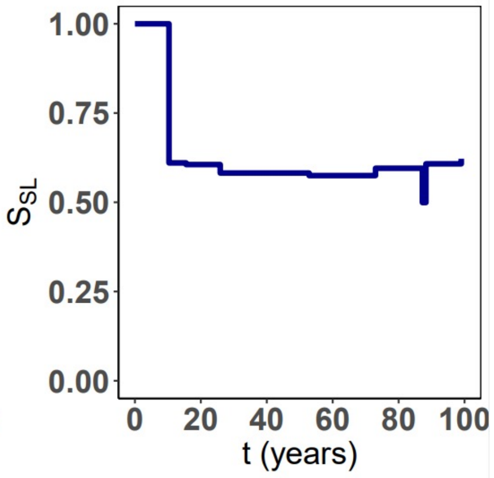
Local scouring width



Bearing capacity stability ratio



Overturning stability ratio



Sliding stability ratio

CASE STUDY 1

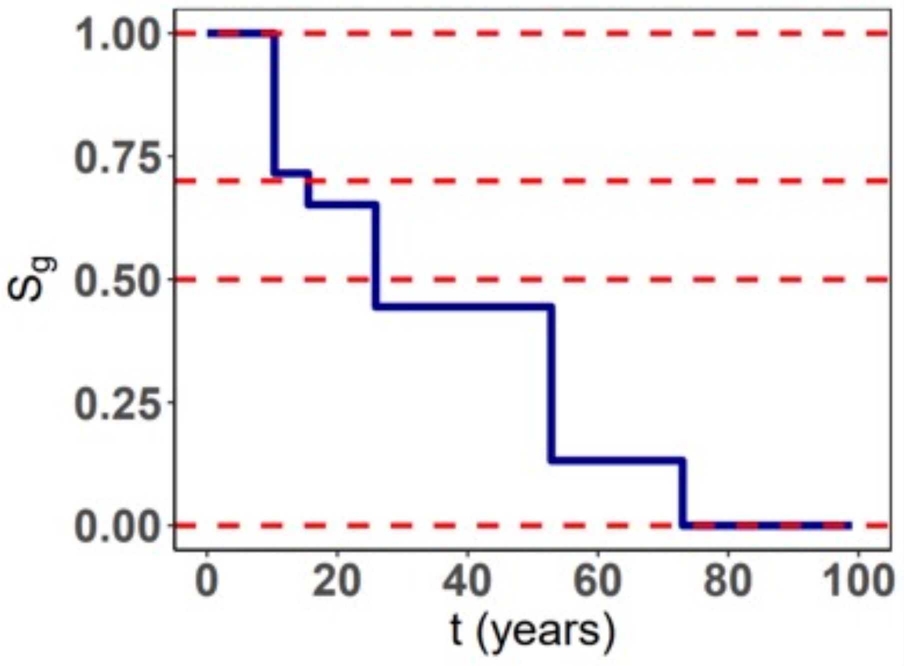
Performance Analysis using the Physics-based model

(Chahrour et al. RESS 2021)

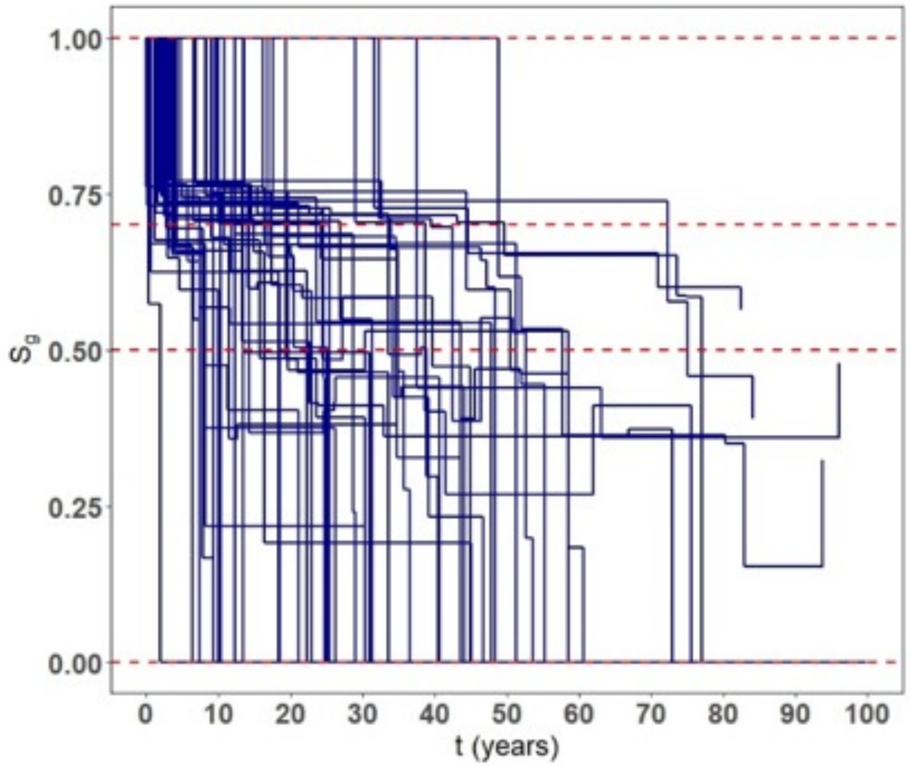
Time-based evolution of the global stability indicator Sg

Check dam #54

Sg corresponding to scenario 1



Sg corresponding to the 50 generated scenarios



CASE STUDY 1

Performance Analysis using the Physics-based model

(Chahrour et al. RESS 2021)

Fitting probability distributions for stochastic transitions

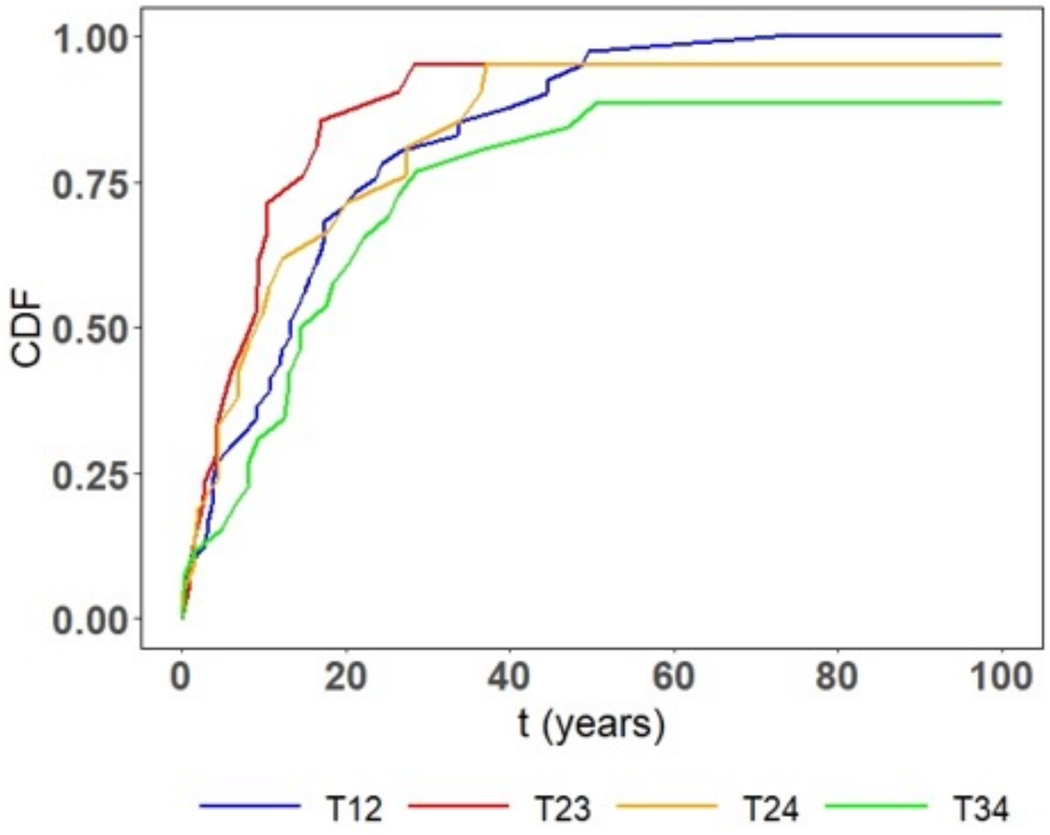
Check dam #54

T12 (41 values)
T23 (20 values)
T24 (20 values)
T34 (23 values)

} Empirical CDF using Kaplan Meier Estimator

T13 (6 values)
T14 (3 values)

} Log normal distribution (μ, σ)



CASE STUDY 1

Performance Analysis using the Stochastic Deterioration & Maintenance Model

(Chahrour et al. RESS 2021)

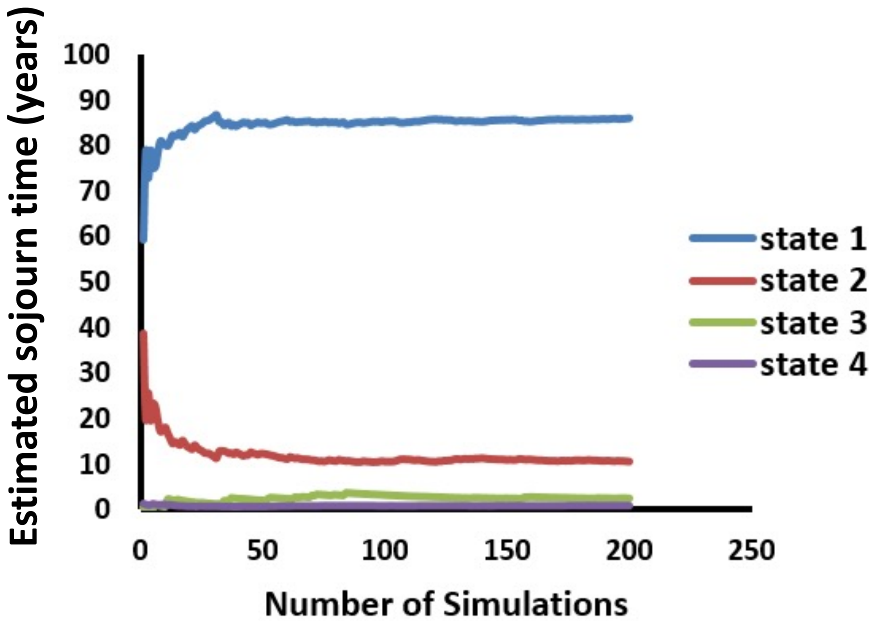
Mean sojourn time spent by the dam in each state

Check dam #54

	State 1	State 2	State 3	State 4
Strategy 1	86.01	10.49	2.55	0.87
Strategy 2	56.62	37.27	4.20	1.77
Strategy 3	73.04	6.73	19.02	1.21
Strategy 4	44.43	25.89	27.45	2.23

(Results provided by the SPN model)

Time spent by the dam in each state - strategy 1.



CASE STUDY 1

Performance Analysis using the Stochastic Deterioration & Maintenance Model

(Chahrour et al. RESS 2021)

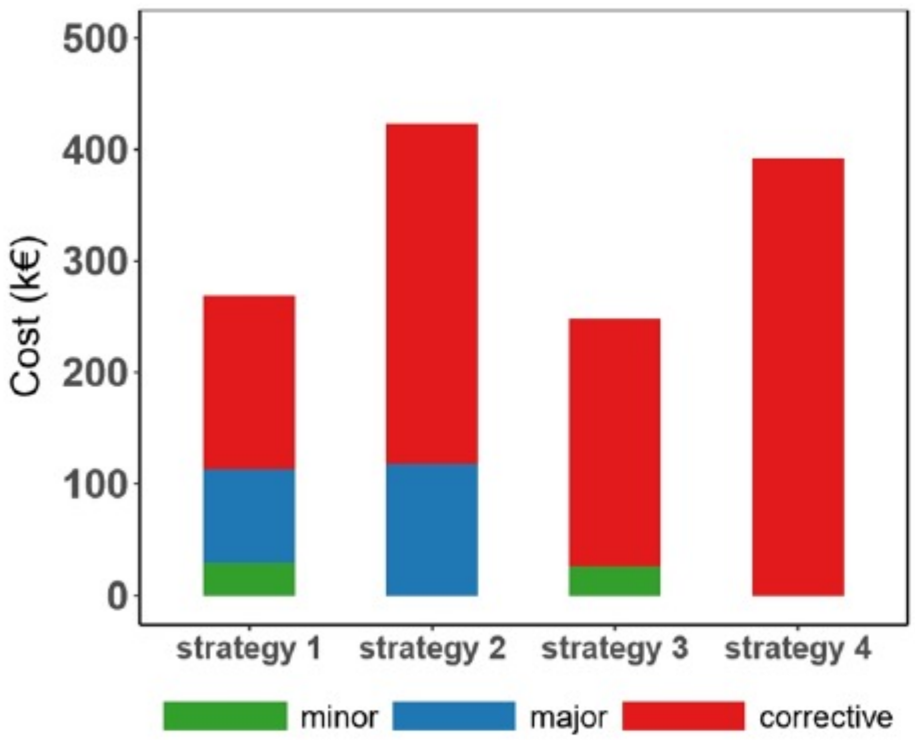
Average number of maintenance operations applied to the dam over a period of 100 years

Check dam #54

	Minor operations	Major operations	Corrective operations
Strategy 1	3.85	1.13	1.04
Strategy 2	0	1.57	2.04
Strategy 3	3.49	0	1.48
Strategy 4	0	0	2.62

(Results provided by the SPN model)

Average expected cost of each maintenance strategy.



CASE STUDY 1

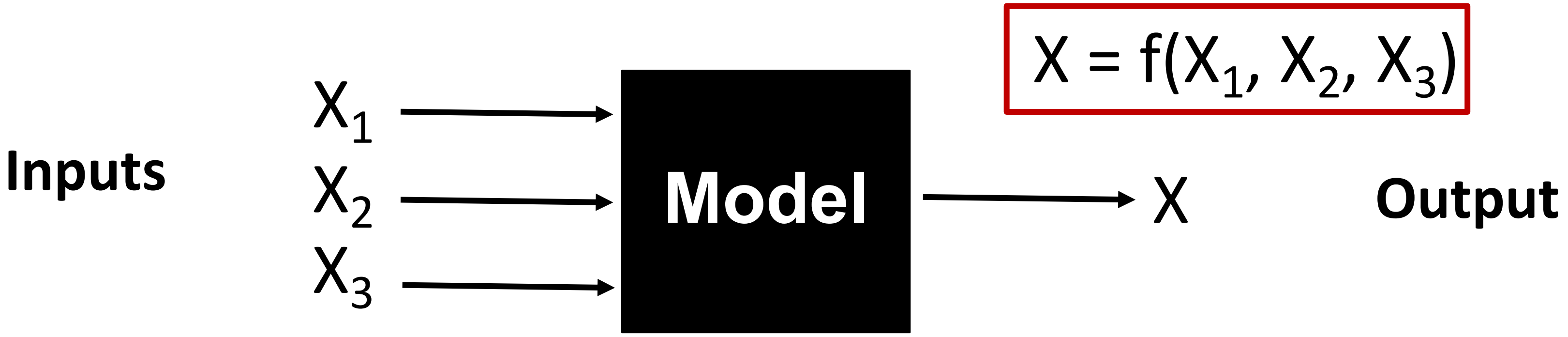
Uncertainty Analysis using HYRISK

Hybrid approach addressing uncertainty in risk context

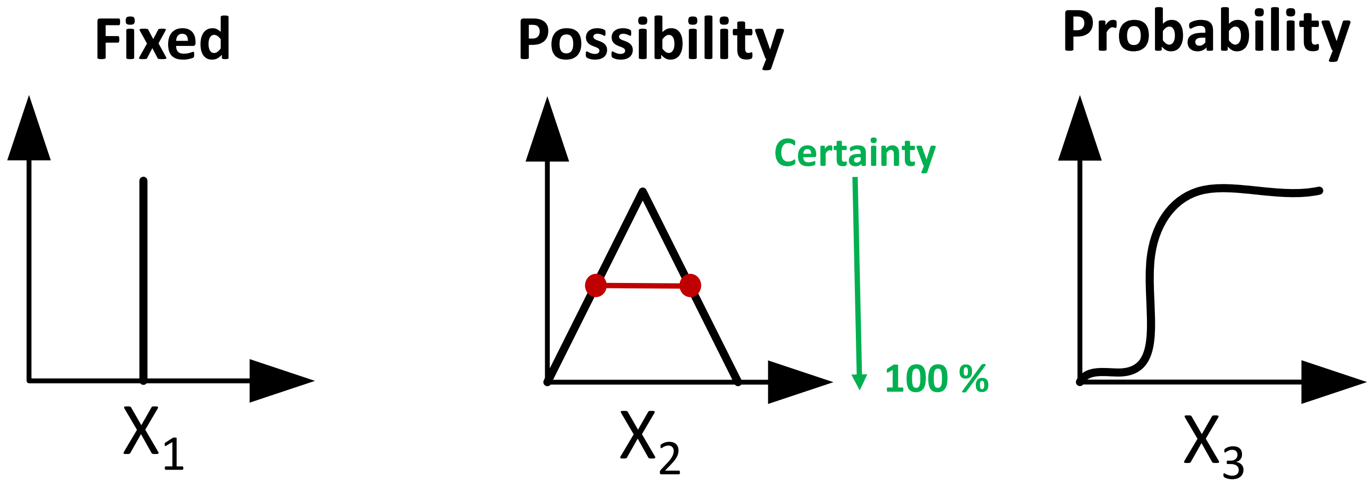
(Rohmer et al., 2018) *(Baudrit et al., 2007)*

1 Uncertainty representation

Define **inputs** and **outputs**



Assign **distributions** for inputs



CASE STUDY 1

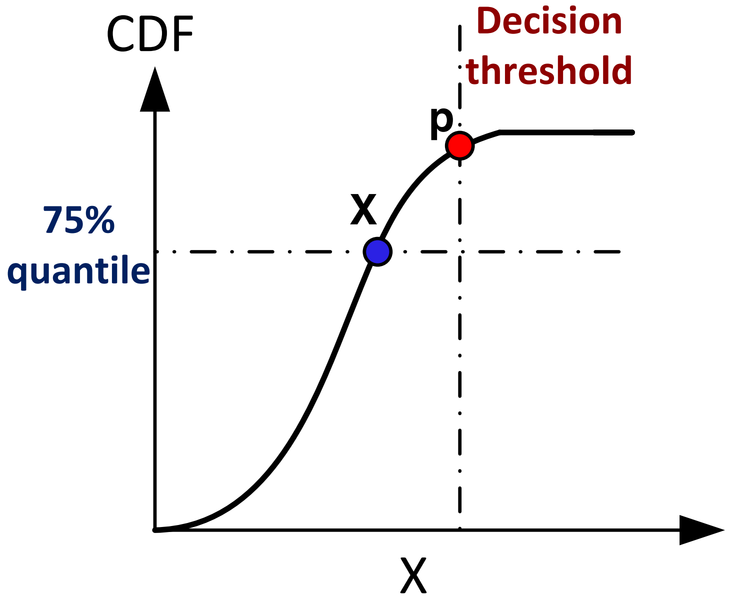
Uncertainty Analysis using HYRISK

Hybrid approach addressing uncertainty in risk context

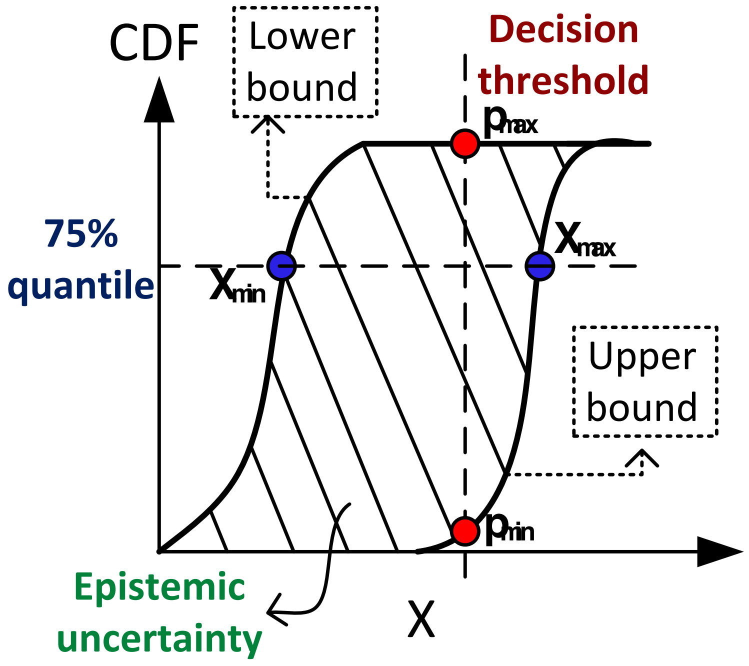
(Rohmer et al., 2018) (Baudrit et al., 2007)

2 Uncertainty Propagation

Case 1 – Uncertain **inputs** are **all** represented as **probability** distributions



Case 2 – **At least one** uncertain **input** is represented as a **possibility** distribution



CASE STUDY 1

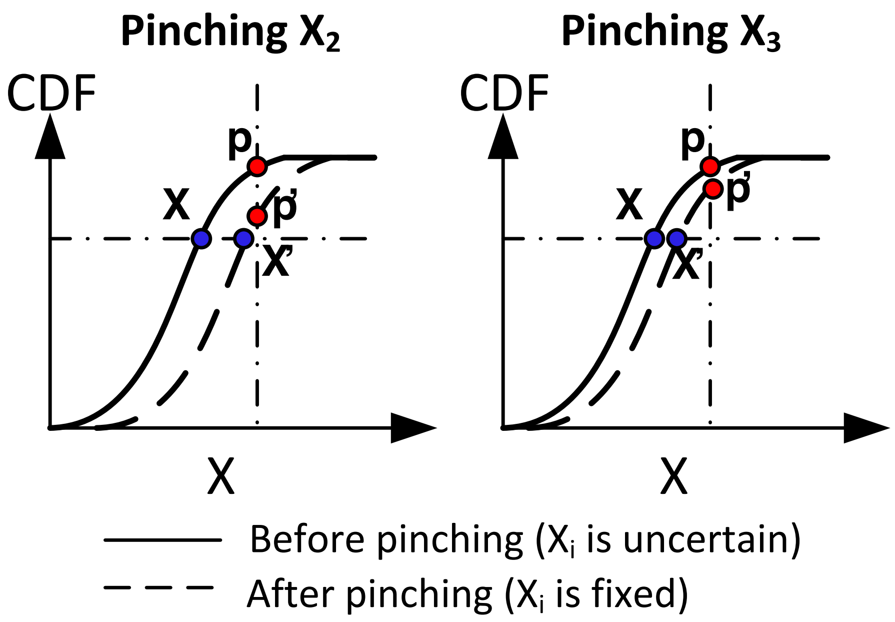
Uncertainty Analysis using HYRISK

Hybrid approach addressing uncertainty in risk context

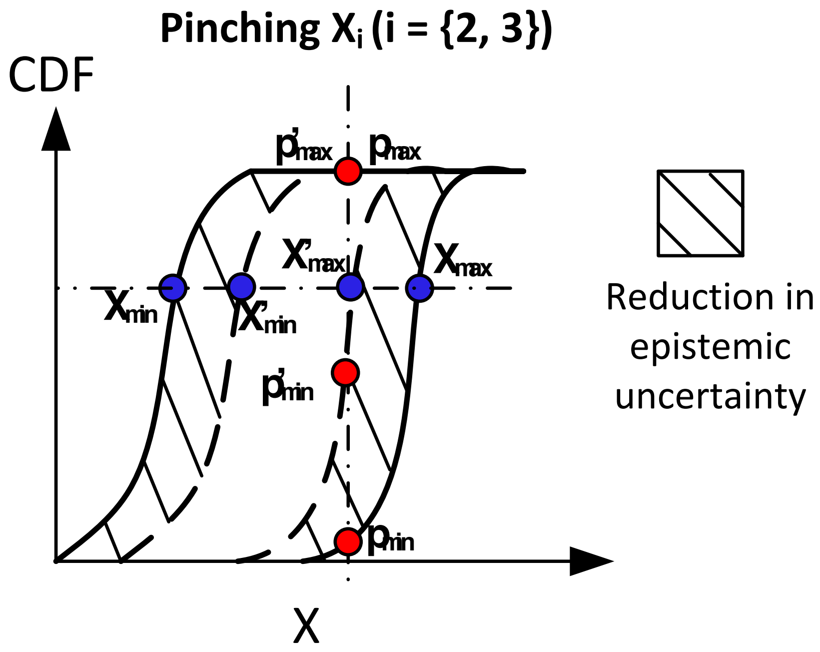
(Rohmer et al., 2018) *(Baudrit et al., 2007)*

3 Sensitivity analysis

Case 1 – Uncertain **inputs** are **all** represented as **probability** distributions



Case 2 – **At least one** uncertain **input** is represented as a **possibility** distribution

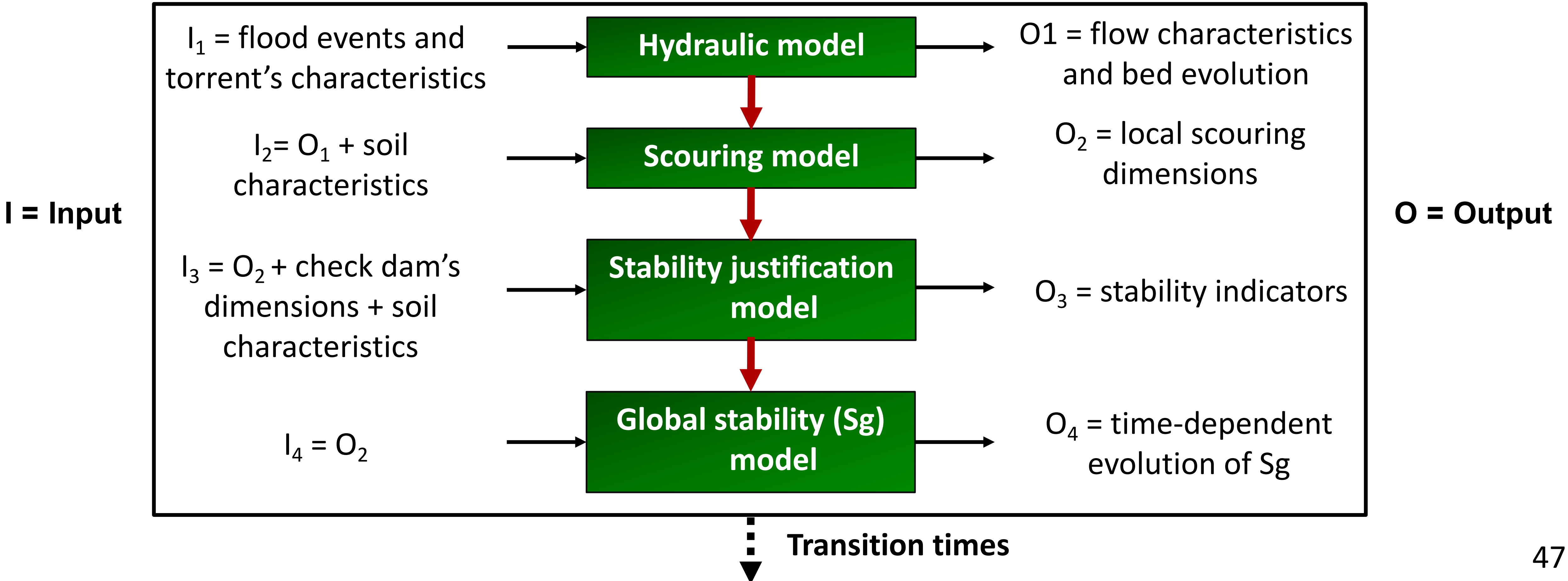


CASE STUDY 1

Uncertainty analysis applied to check dam model

(Chahrour et al. ESREL 2021)

Sub-models of the physics-based model

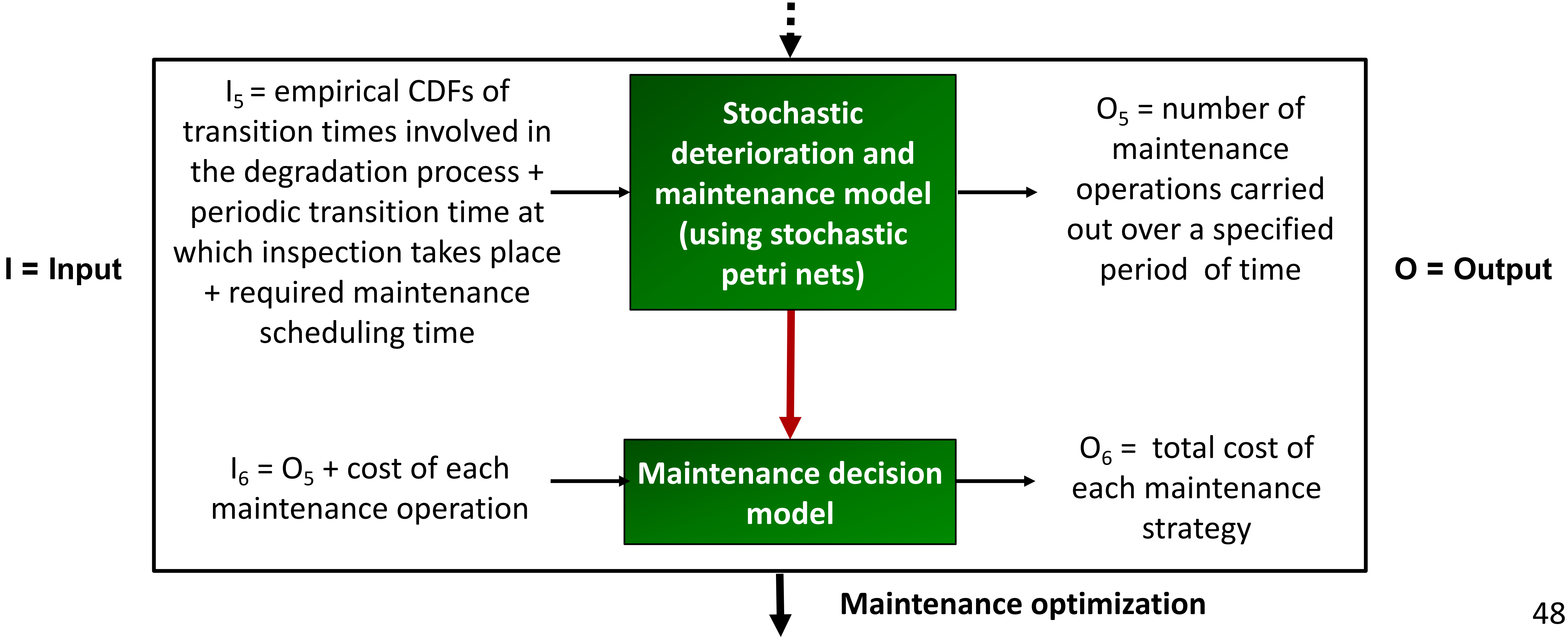


CASE STUDY 1

Uncertainty analysis applied to check dam model

(Chahrour et al. ESREL 2021)

Sub-models of the stochastic deterioration & maintenance model



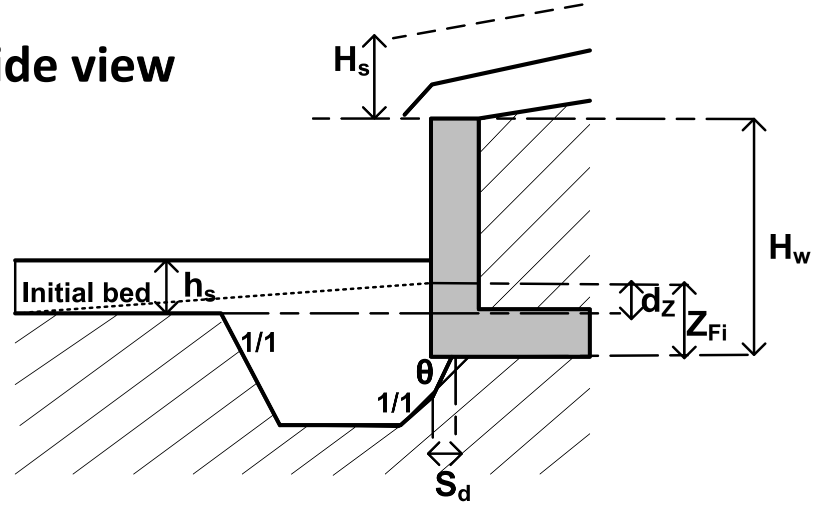
CASE STUDY 1

Uncertainty analysis applied to check dam model

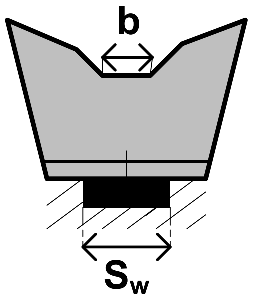
(Chahrour et al. ESREL 2021)

Scouring estimation sub-model

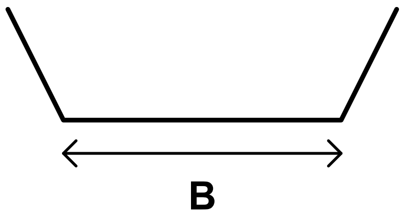
Side view



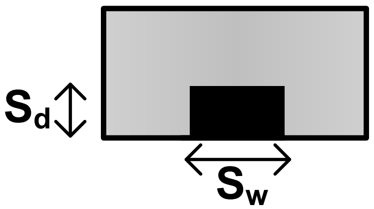
Front view



Transverse profile



Bottom view



Variable inputs

$$S_d = f(H_s, h_s, B, D_{90}, Z_{Fi}, d_z, \Delta, H_w, b, \theta)$$

$$S_w = f(H_s, h_s, B, D_{90}, Z_{Fi}, d_z, \Delta, H_w, b)$$

Fixed inputs

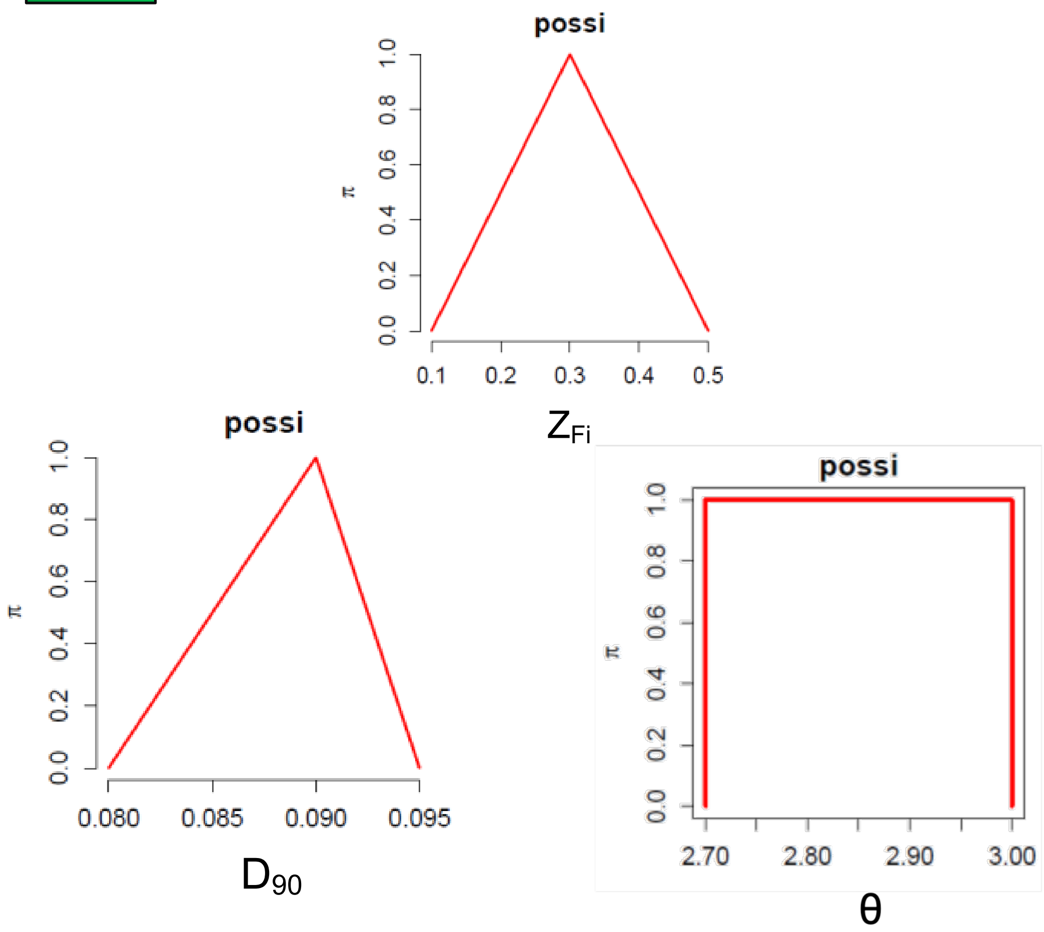
Input	H_s (m)	h_s (m)	B (m)	d_z (m)	Δ	H_w (m)	b (m)
Value	0.737	0.229	6	0.873	1.65	2.3	4.4

CASE STUDY 1

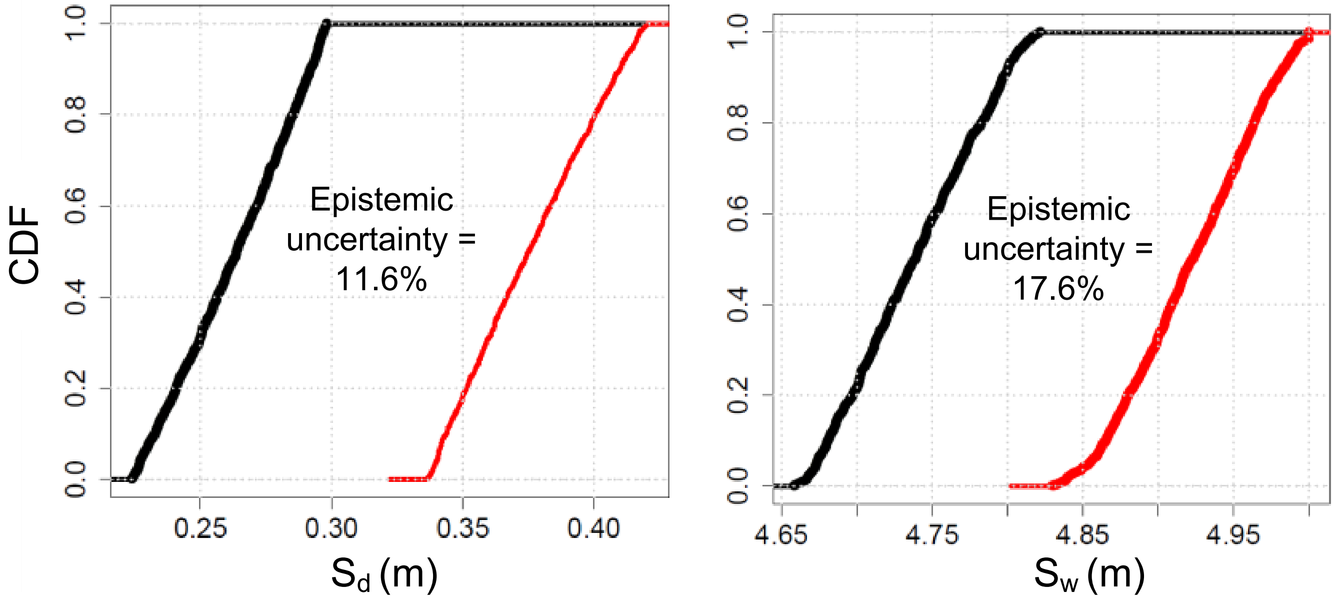
Uncertainty analysis applied to check dam model

(Chahrour et al. ESREL 2021)

1 Uncertainty representation



2 Uncertainty propagation

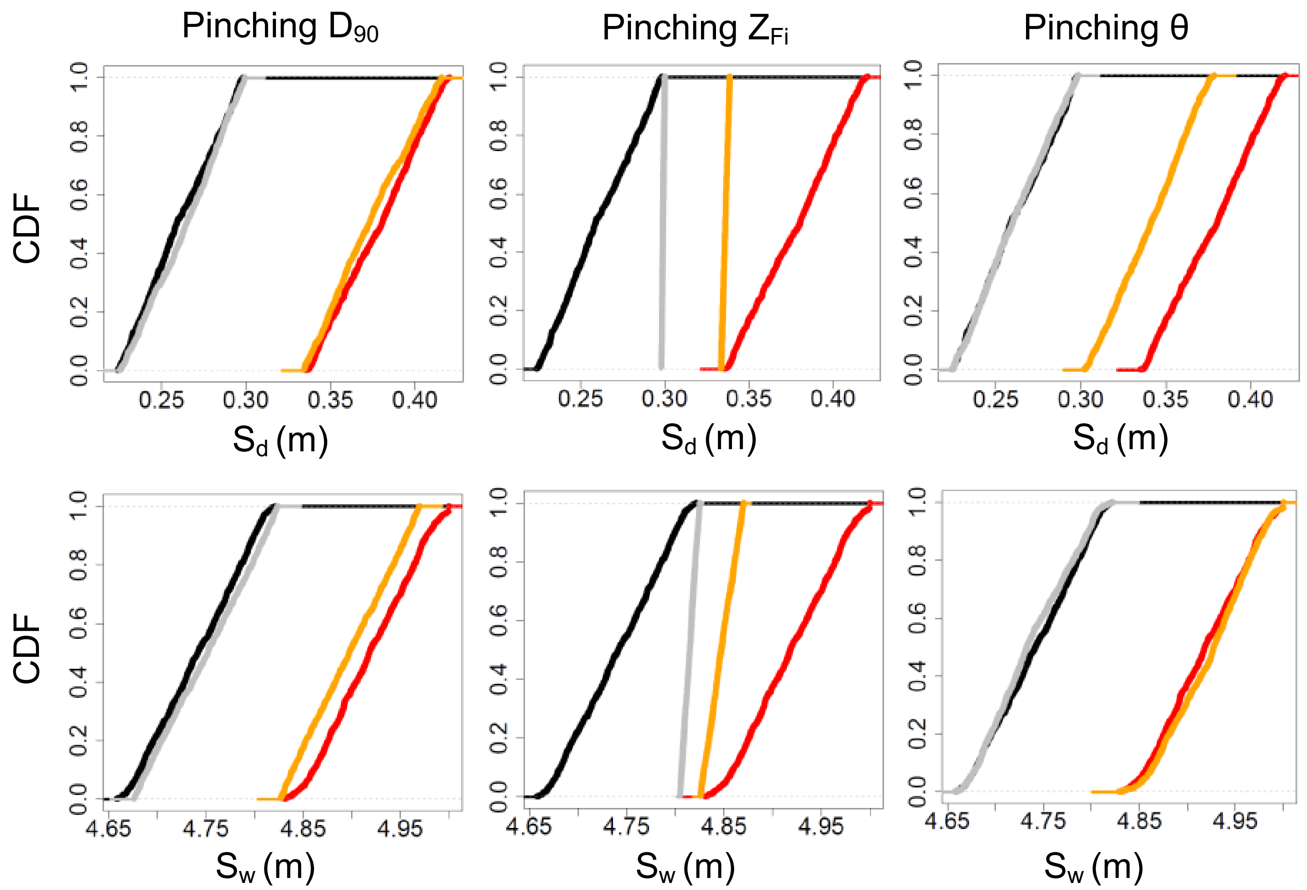


Uncertainty analysis applied to check dam model

(Chahrour et al. ESREL 2021)

3 Sensitivity analysis

Fixed values $D_{90} = 0.09$ m $Z_{Fi} = 0.3$ m $\theta = 3$ m/m



Epistemic uncertainty (%)

Output	Uncertainty propagation	Pinched input parameter		
		D_{90}	Z_{Fi}	θ
S_d	11.60	10.84 *6.55%*	3.67 *68.36%*	7.93 *31.63%*
S_W	17.60	14.56 *17.27%*	3.36 *80.90%*	17.60 *0%*

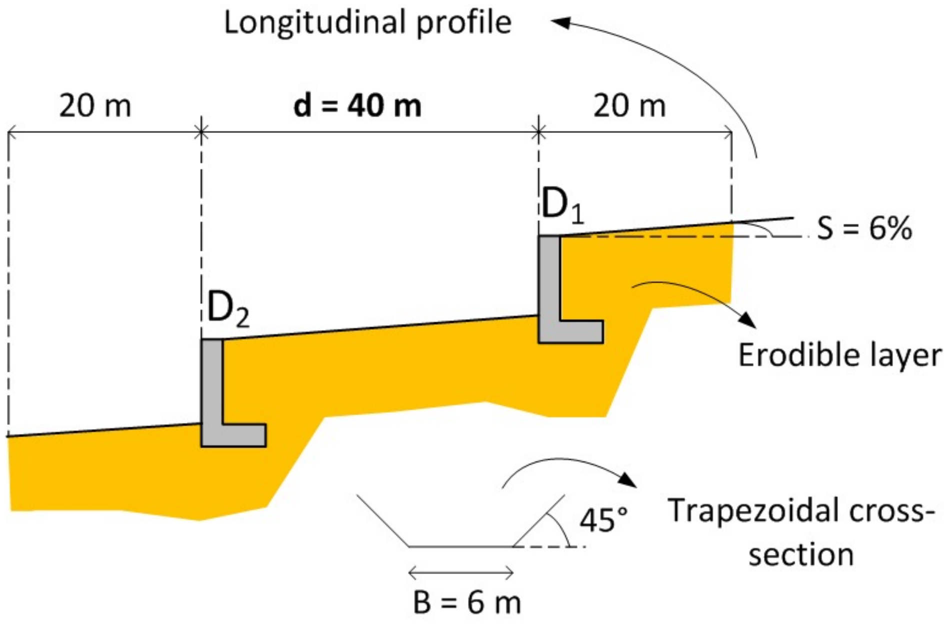
S_d and S_w are more sensitive to the epistemic parameter Z_{Fi}

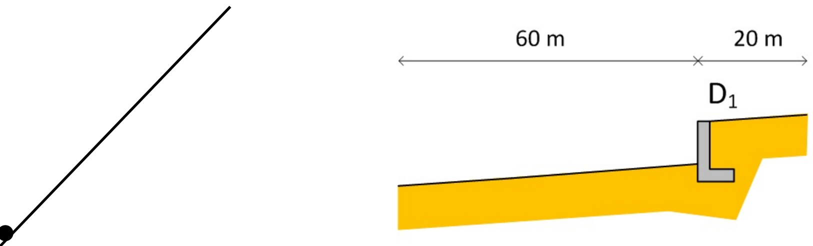
CASE STUDY 2

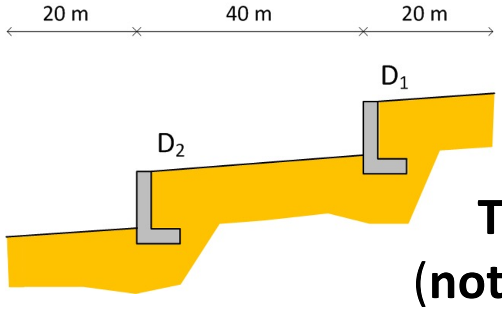
Multi-component system: Bi-directional dependencies

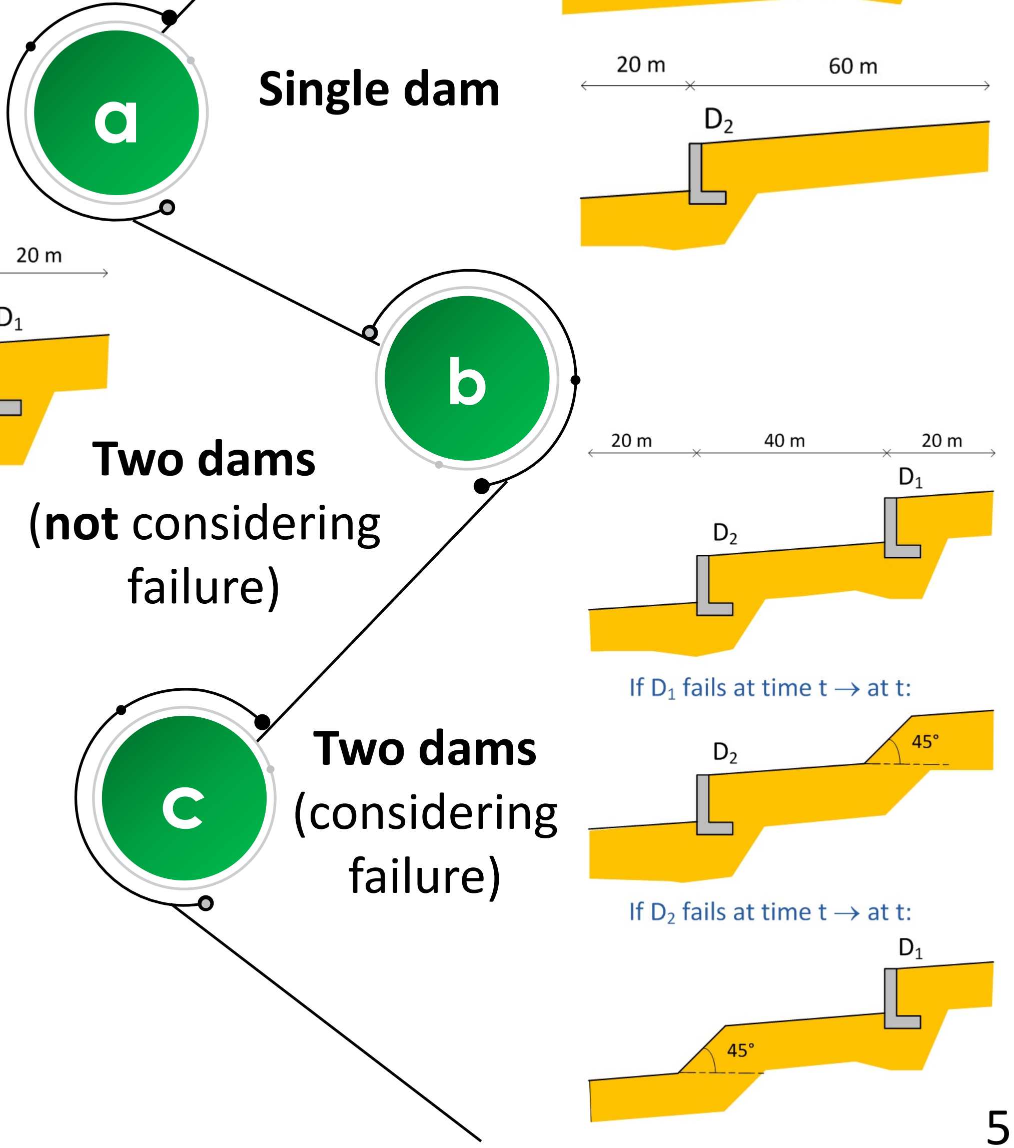
(Chahrour et al. RAMS 2021)

Three cases to be **modeled** over a period of **50 years**









CASE STUDY 2

Performance & Dependency Analysis using the Physics-based model

(Chahrour et al. RAMS 2021)

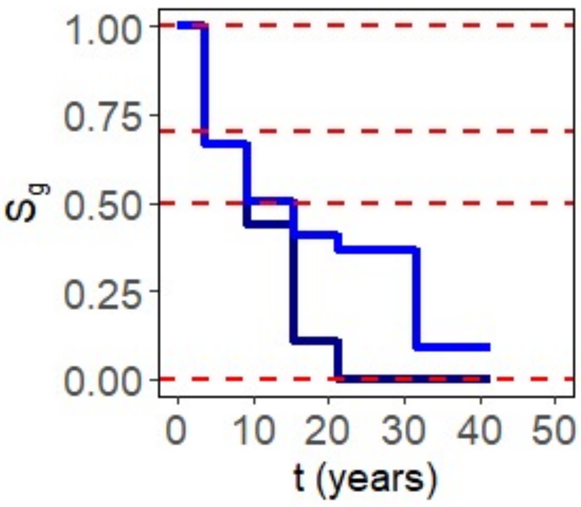
D_1 fails first

Global stability index evolution over time

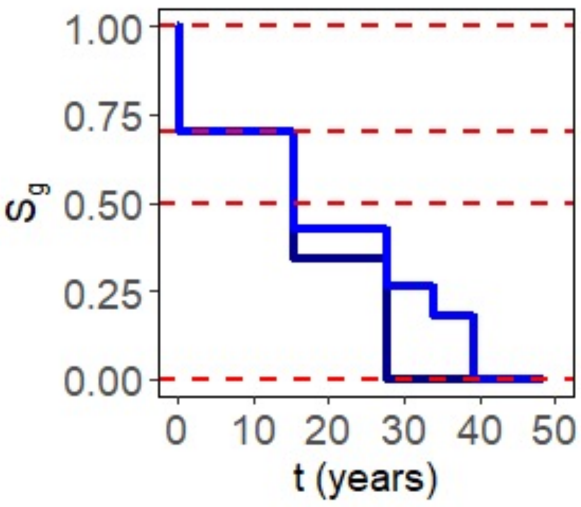
Absence of D_2 (lower stability)

Presence of D_2 (higher stability)

Scenario i

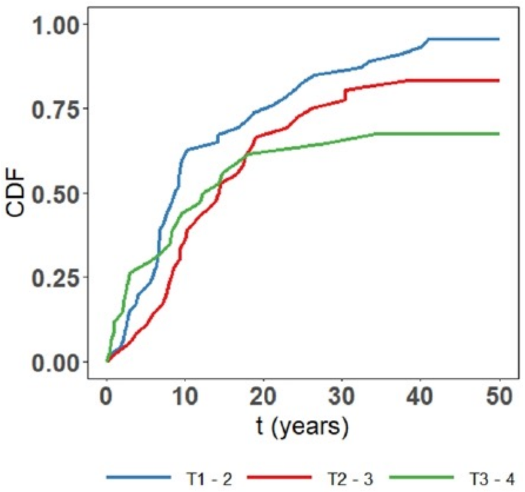


Scenario j

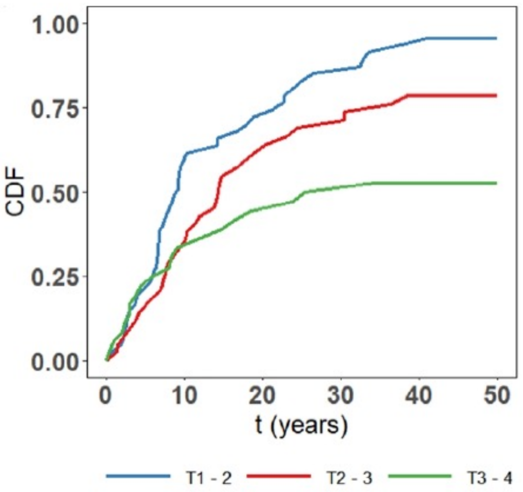


Cumulative distribution function of stochastic transitions $T_{1\text{-}2}$, $T_{2\text{-}3}$, and $T_{3\text{-}4}$

Absence of D_2



Presence of D_2



Transitions with few number of observation (N): $T_{1\text{-}3}$ and $T_{2\text{-}4}$

~ Exponential distribution ($\lambda = 1/N$)

CASE STUDY 2

Performance & Dependency Analysis using the Stochastic Deterioration & Maintenance Model

(Chahrour et al. RAMS 2021)

SPN model applied only to D_1

Mean sojourn time (years) of D_1 in each state over a period of 50 years

Absence of D_2

	State 1	State 2	State 3	State 4
Strategy 1	44.65	4.95	0.27	0.04
Strategy 2	26.02	23.00	0.63	0.15
Strategy 3	41.20	4.13	4.42	0.13
Strategy 4	20.82	19.37	9.18	0.39

Presence of D_2

	State 1	State 2	State 3	State 4
Strategy 1	44.06	5.59	0.26	0.02
Strategy 2	24.03	24.44	1.35	0.06
Strategy 3	40.11	4.72	4.96	0.11
Strategy 4	18.43	18.69	12.45	0.26

Almost same results

CASE STUDY 2

Performance & Dependency Analysis using the Physics-based model

(Chahrour et al. RAMS 2021)

SPN model applied only to D_1

Average expected number of maintenance operations over a period of 50 years

Absence of D_2

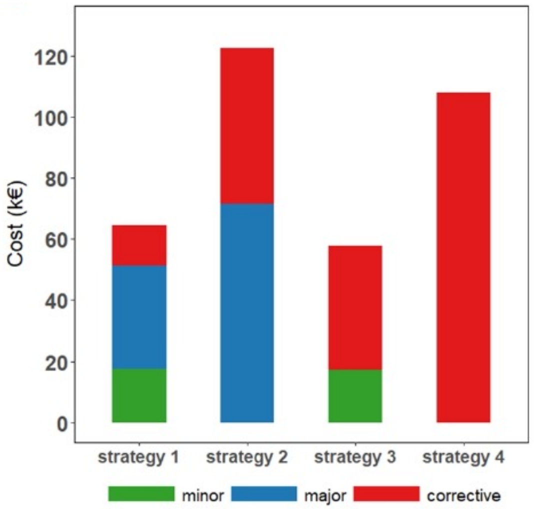
	Minor operations	Major operations	Corrective operations
Strategy 1	2.37	0.45	0.09
Strategy 2	0	0.96	0.34
Strategy 3	2.31	0	0.27
Strategy 4	0	0	0.72

Presence of D_2

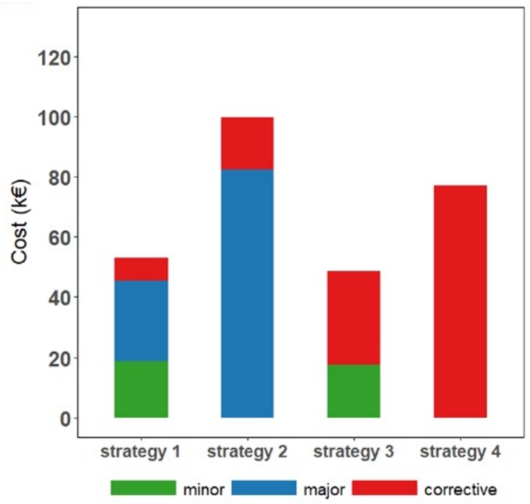
	Minor operations	Major operations	Corrective operations
Strategy 1	2.51	0.36	0.05
Strategy 2	0	1.10	0.12
Strategy 3	2.37	0	0.21
Strategy 4	0	0	0.52

Total cost of each maintenance strategy

Absence of D_2



Presence of D_2



Strategy 3 is the most cost-effective

OUTLINE

Achieved Contributions

Objectives:

- Analyze different **behavioral scenarios** of protection structures subjected to deterioration mechanisms and maintenance operations
- Make **cost-effective** maintenance decisions.

Achievements:

- **Integrated modeling approach**:
  - Physics-based model (dynamic state evolution, transition times)
  - Reliability-based stochastic model (stochastic deterioration and maintenance modeling)
- **Performance analysis** of protection structures (case studies on check dams and retention dam)

General Discussion

From a **research point of view** :

- A **multidisciplinary approach** that combines several fields in order to support decision-making based on raw data and expert knowledge.
- A **new decision-support approach** (dynamic over their lifetime, dependencies) to support their **maintenance** decision-making
- **Coupling** multi-scale **hydraulic** analysis (from global bed evolution to check dams' local scouring analysis) and **civil engineering** approaches (stability analysis).
- **Coupling physics-based** (hydraulic and mechanical) models with **reliability**-based models (SPNs, CBM) in order to **justify transition laws** involved in the stochastic **degradation process**.

CONCLUSION

General Conclusions on Achieved Contributions

From an operational point of view :

- **Realistic** and **informative approach** that supports risk managers and decision-makers to make optimal management decisions.

- **Feedback** on **real life behavior** of the protection structures concerning real maintenance strategies

- Totally **generic approach**: applicable to any civil engineering structure exposed to any undesirable phenomena.

PERSPECTIVES

Limitations and Future Work

For physics-based model:

- **Developing** the **global state indicator** by considering aging aspects and more types of failures.
- Carrying out **more research** and **technical analysis** in order to better choose the **degradation states' thresholds**.

For the stochastic deterioration and maintenance model:

- Considering **partial renewal maintenance** actions instead of perfect ones.

For bi-directional dependency analysis in a Multi-component system:

- Applying the model to a real case study where **real data** is available.
- Considering **more components** in the system.

PERSPECTIVES

Limitations and Future Work

For uncertainty analysis:

- **Propagating uncertainty** using HYRISK **within the whole model** in order to be aware of how it may eventually affect the maintenance decision.
- Re-estimating transition laws taking into account (i) **climate change** and (ii) **topographical changes**.

Other developments:

- Analyzing the **efficiency** of adopted **maintenance strategies** on the maintained structure itself.
- Assessing the economic efficacy by estimating the **risk imposed on downstream elements**.
- Taking into account the **monetary evolution** over time instead of constant maintenance costs.

QUESTIONS?

Thank You

nour.chahrour@inrae.fr