



**HAL**  
open science

# A timeline computer framework for the representation of multi-scale Human-Nature interactions

Isabelle Charpentier, Lise Pinault

► **To cite this version:**

Isabelle Charpentier, Lise Pinault. A timeline computer framework for the representation of multi-scale Human-Nature interactions. 2023. hal-04096908

**HAL Id: hal-04096908**

**<https://hal.science/hal-04096908v1>**

Preprint submitted on 14 May 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# A timeline computer framework for the representation of multiscale Human-Nature interactions

Isabelle Charpentier<sup>a,b</sup>, Lise Pinault<sup>c</sup>

<sup>a</sup>ICUBE (UMR7357), CNRS&Unistra, 2 rue Boussaingault, 67000 Strasbourg, France.

<sup>b</sup>LTSER-FR Zone Atelier Environnementale Urbaine, MISHA, 5 allée du Général Rouvillois, 67000 Strasbourg, France

<sup>c</sup>Chrono-Environnement (UMR6249), Université de Franche-Comté, 16 route de Gray, 25000 Besançon, France.

---

## Abstract

Any river describes a trajectory and models its riverine ecosystems. This poetic view undoubtedly underestimates the anthropic management effects. The long term social ecological research describes social and biogeophysical components and their interrelations in qualitative terms, long term observations and dynamical systems offering complementary quantitative information. For a specific territory, this heterogeneous information may be aggregated into a social ecological timeline to provide an overall outlook of the evolution of the Human-Nature interactions.

Drawing a timeline remains a painful task, especially when it should be adapted to the introduction or to the reorganization of some piece of information. ZATimeline is a real-time software dedicated to the representation and the analysis of social ecological systems by means of a timeline. The framework relies on formatted spreadsheets manageable with an Office suite and a graphical user interface to facilitate the uptake by students, researchers and stakeholders, notably during workshops. The Upper Rhine river and the Rohrschollen island are chosen as a case study to assess the interest of timelines compared to other conceptual frameworks, and to answer important questions about the adaptive management and the naturalness of both the river and the Rhenan alluvial forests.

*Keywords:* Long term social ecological research, Social ecological system, Adaptive management, Trajectory representation, Upper Rhine river, Rhenan alluvial forests.

---

## 1. Introduction

Since the seventies, the limits to growth (Meadows et al., 1972) and the impacts of human activities on ecosystem activities are stated at local, national and world scales. Questions about the worthiness of Nature's services (Westman, 1977), the valuation of ecosystem services (Daily, 1997) or the conservation biology (Costanza et al., 1997) exemplify this raise of ecology awareness.

The Millennium Ecosystem Assessment (World Resources Institute, 2005) was conducted to provide stakeholders, decision makers and the general audience with scientific information about the consequences of ecosystem change on human well-being. Today, in a context of climate, energy and biodiversity crises, the water–food–energy nexus is at the heart of a sustainable development as these resources are managed, produced and extracted from ecosystems.

Concurrently, vocabulary and models have evolved. Frameworks such as social ecological conceptual

schemes (Collins et al., 2010; Haines-Young and Potschin, 2010; Bretagnolle et al., 2019) or Nature's contribution to people (Díaz et al., 2018) tend to replace the anthropocentric concept of ecosystem services.

Given a territory, the long term social ecological research describes social and biogeophysical components and their interrelations in qualitative terms. Sometimes, ecosystems and human-nature interactions may be modeled by a dynamical system (Meadows et al., 1972; Holling, 1978), the solutions of which are compared to time series of some biogeophysical variables or indicators in a quantitative manner. The temporalities of the geographical spaces (Elissalde, 2000) and their ecosystems may also be represented on social ecological timelines (Bergeret et al., 2015; Arnaud, 2019) Arnaud et al. (2022).

The hydraulic projects carried out along the Rhine river (French-German border) (Uehlinger et al., 2009; Tricart and Bravard, 1991; Eschbach et al., 2018) during the last two centuries have profoundly modified the flood plain and impacted the Rhenan alluvial fo-

rests, questioning the contemporary evolution of these forests and the naturalness of the Rohrschollen island. The changes in governance (Doerflinger, 1987; Euro-métropole de Strasbourg, 2018a), the land cover and the risks, for instance, are highly valuable but heterogeneous information to be organized prior to the analysis of social ecological trajectories.

The paper focuses on their timeline representation by means of the ZATimeline software, and a follow-up testing of nested social ecological systems (SESs) within the Upper Rhine graben. A particular attention is brought to the river, the aquifer and some other smaller water bodies with regards to management plans and climate change.

The layout of the paper is as follows. Social ecological schemes, adaptive cycles and timelines are discussed in Section 2 by emphasizing similarities and differences. By means of computer science tools, Section 3 aims to conciliate the representation of these qualitative schemes, long term observations, some trajectories of dynamical systems and timeline charts. The case study and results are presented and discussed in Sections 4 and 5, respectively. A conclusion and an outlook are proposed in Section 6.

## 2. Modeling SESs

The notion of ecosystem is introduced by Tansley (1935). Human activity is described as a powerful biotic factor, able to disturb ecosystems' equilibrium, or even to ruin them. Anthroposystems (Lévêque et al., 2000) and SES (Collins et al., 2010) were proposed to objectify human roles within the ecosystems models, see subsection 2.1.

Dynamical systems based on variables and the parameterization of their interactions offer another point of view (Meadows et al., 1972; Holling, 1978). Usually, the states of a system may be partly observed along time through some long term data collection. These are used to improve the model, then to estimate some missing information or to predict a long term evolution.

The diversity and the complexity of the interactions between humans and ecosystems result in complex problems, today qualified as "wicked" for their many interdependent components (Davies et al., 2015). Their number, their spatial and temporal scales, the level of knowledge, heterogeneity and uncertainty are among factors that reasonably prevent an exhaustive modeling. Timelines were proposed to represent this heterogeneous information (Elissalde, 2000), see subsection 2.2.

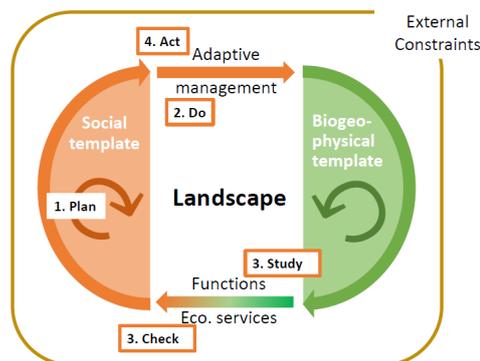


FIGURE 1 – Conceptual scheme together with the PDS (Shewhart cycle) and PDCA (Deming wheel) actions.

### 2.1. Conceptual schemes

The interrelations between the environment and the society are of complex modeling. Conceptual schemes proposed in (Collins et al., 2010; Bretagnolle et al., 2019) may be viewed as a two-body system, the elements of which are a social model and a biogeophysical model, see Fig. 1. In (Bretagnolle et al., 2019), these are interacting through an adaptive management interface and an ecosystem interface ranging from the environmental functions to the benefits for the society, passing through ecosystem services. Similarly, the cascade model (Haines-Young and Potschin, 2010) describes the Nature-Human interface from a central bio-geophysical element. It specifies the functions, the ecosystem services and the benefits it provides to the society. Social or environmental pressures and mitigation actions are operating as a feedback.

The conceptual scheme is drawn in Fig. 1 together with the phases involved in iterative management frameworks, namely Shewhart cycle (Shewhart, 1939) and Deming wheel (Deming, 1982), for the control and continual improvement of industrial processes (Moen and Norman, 2010). The "Plan-Do-Study-Act" (PDSA) acronym agrees well with the long term social ecological research (LTSER). The adaptive cycle (Holling, 1978) or the adaptive management of natural resources (Williams, 2011) may be viewed as their environmental version. The reader is referred to (Sendzimir et al., 2018) for a discussion about the adaptive management of riverine socio-ecological systems.

The panarchy framework (Holling, 1978) is a set of nested models that emphasizes different levels of spatial and temporal scales and their interrelations. A similar approach is promoted in (Elissalde, 2000) for geography. Figure 1 may be already viewed as a panarchy comprising two small loops within the social and bio-

geophysical templates to represent internal processes, the main SES loop, and the external constraints (climate, national regulations, international agreements).

## 2.2. Social-ecological timeline

As quoted in (Sheps, 1999), the use of the charts was the “most excellent mechanical help to the knowledge of history, impressing the imagination indelibly with a just image of the rise, progress, extent, duration, and contemporary state of all the considerable empires that have ever existed in the world”.

The temporalities of the geographical space (Elisalde, 2000) and their ecosystems may be represented on timelines (Bergeret et al., 2015; Arnaud, 2019) Arnaud et al. (2022). The horizontal lines convey an idea of the duration of influence, domination or breakdowns, while the vertical reading may sort information with respect to either the elements of a conceptual scheme, or the scales in a panarchy representation, see subsection 4.2.1.

A timeline is an efficient diagram to figure out the dynamics in an ecosystem or a SES. It allows for the visualization and the analysis of heterogeneous information (events, trends, constraints, and so forth) and their interrelations. When available, a timeline can be compared to time series to support a quantitative or a qualitative analysis. Note that voids in the chart may help to identify lacks of data or interdisciplinary gaps.

Many uses are targeted. Social ecological timelines were used as mediation tools during workshops with local stakeholders (Bergeret et al., 2015; Bruley et al., 2021)Guerbois et al. (2020). More generally, timelines allow for the adaptive management, the reporting on activities, and the assessment of scenarios. The timeline information may be organized into a database to be made available to a large audience through an interactive web-site (Arnaud, 2019).

Drawing a timeline remains a painful task, especially when it should be adapted to the introduction or to the reorganization of some piece of information. Among the software dedicated to project management, Office Timeline pro builds on PowerPoint and a formatted Excel spreadsheet to produce timelines and Gantt charts. Here again, adaptive management in economy and social ecological research may use similar methods.

## 3. Computer-aided design

By means of some computer science tools, this section aims to aligns the qualitative schemes of section

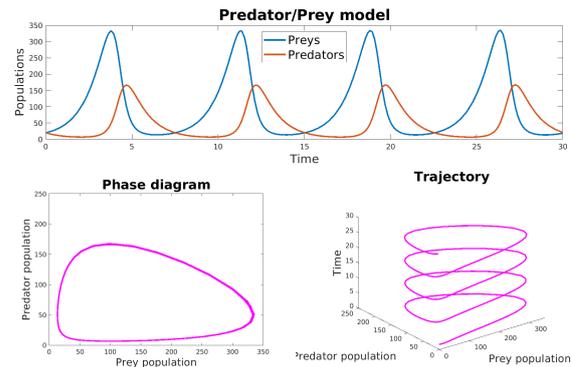


FIGURE 2 – Three views of the trajectory of a prey-predator model.

2, the long term qualitative and quantitative observations, and the computed trajectory of dynamical systems. The ZATimeline software dedicated to the representation and the data management of social ecological information on a timeline is then presented.

### 3.1. Trajectory and cycles

Trajectory is a scientific word derived from Latin and created by Isaac Newton to describe the paths of bodies (revolving orbits) traveling through the space by means of mathematical equations. In physics, the trajectory of a point (or the centroid of a system) describes its successive positions in a given coordinate reference system. Assuming that a central element may be identified or chosen within a SES, the same definition could be applied. Otherwise one may represent the trajectories of some of its components.

The prey-predator (Lotka-Volterra) model and the Lorenz attractor are used to illustrate stable and unstable behaviors.

An example of the prey-predator equations may be run using Matlab online. Figure 2 proposes three different views for the solution of the prey-predator equations computed with parameters  $\alpha = 0.02$  and  $\beta = 0.01$ . The top picture shows the trajectories of the variables. These could be compared with long term observations. The phase diagram is a projection that eliminates time by plotting one variable against the other. It can be used to exhibit cycles. For this two-dimensional system, the trajectory is a three-dimensional curve (space and time). In this example, the trajectory exhibits a periodic behavior that may result in a sustainable cycle (stable equilibrium) either in the absence of perturbations or in an adaptive management process.

As an illustration of chaos, the Lorenz attractor was built to behave in a different manner. Some results of the Lorenz model run with the parameters  $\rho = 28$ ,  $\sigma = 10$ ,

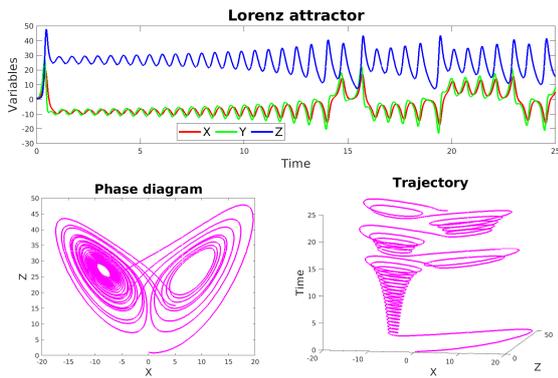


FIGURE 3 – Three views of the trajectory of a Lorenz attractor.

$\beta = 8/3$  (Moiseev, 2023) are plotted in Fig. 3. The phase diagram exhibits the famous butterfly corresponding to unstable equilibria. In that sense, one may recognize a representation of the Holling’s adaptive cycle.

Social ecological models are usually multi-scalar ill-conditioned/wicked problems. Under a number of assumptions, simplified quantitative dynamical modeling could be carried out. For example, as the companion model for the “Limits to growth” (Meadows et al., 1972), the WORLD 3 model describes the interactions between natural resources and population through flux loops, resulting in exponential growth curves for both resource consumption and population.

The qualitative modeling is another manner to address social ecological questions about adaptive management and sustainability.

### 3.2. Timelines for heterogeneous data

ZATimeline is a real-time software dedicated to the representation and the analysis of SESs by means of a timeline gathering heterogeneous data. This builds on the Matlab’s programming environment for the graphical user interface (GUI) and the plots Charpentier (2020). The method comprises five steps.

- *Collection.* Data related to events, time series, indicators, trends are welcome to support the social ecological modeling. Information about practices and ecosystem services are of particular interest. Such quantitative and qualitative heterogeneous data are collected in different media (scientific publications, gray literature, maps, photos, inventories, time series...) using different methods (bibliography, mapping, interviews).
- *Encoding.* Any data may be qualified (name), dated (time) and located. Heterogeneous data are thus organized into a spreadsheet, the columns of which

are NAME, START and END dates. An extra column is used to provide STYLE elements for the timeline and the legend plots. Additional data such as location, comments or sources may be considered. Labels may be used to draw links between data.

This formatted spreadsheet is stored into a CSV file. This can be considered as a boundary object between the user and ZATimeline. In particular, tabular data may be sorted or reorganized using tools like Excel or LibreOffice.

- *Representation.* ZATimeline comes with a GUI and a user guide. Spreadsheet data are interpreted and plotted in a sequential manner as colored points, long triangles or rectangles following the user-defined STYLE information.

The GUIs of both the spreadsheet software and ZATimeline have facilitated the uptake by students, researchers and practitioners from a wide variety of disciplines as demonstrated by the studies conducted Alignier et al. (2020); Cognard et al. (2020); Guerbois et al. (2020).

ZATimeline’s GUI allows for real-time data collection and representation in workshops.

- *Analysis.* The timeline plot is analyzed in form and substance. The horizontal temporal axis conveys information on duration, trends and breakdowns. The vertical reading may focus on the components of a SES like actors, practices or services, as modeled in the conceptual scheme (Fig. 1).

The variety of the data is an indicator of the scientific focus and the expertise of the timeline contributors. Voids in the chart may indicate some lacks of inter- or trans-disciplinarity.

Tipping points may be identified and considered to figure out phases on the timeline.

Using the spreadsheet software, the data may be reshaped by inverting lines, sorting or extracting information for a more concise view. The ZATimeline GUI allows for new real-time plot.

- *Metadata and data publication.* ZATimeline is built and distributed to promote FAIR principles (Wilkinson et al., 2016) in the collection of social ecological timeline datasets. The formatted spreadsheets as well as the timeline chart may be deposited in a data repository, see (Charpentier, 2023) for instance.

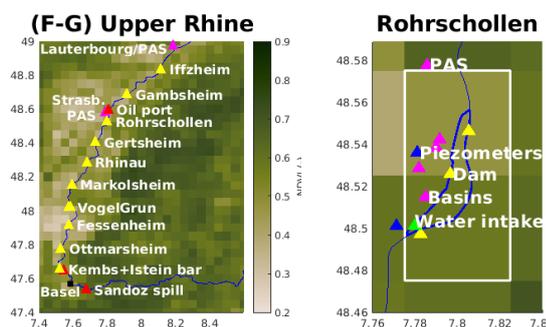


FIGURE 4 – Left : HPPs located on the French-German Upper Rhine border (188 km long). Right : Rohrschollen island (6.3 km long). Background : NDVI data of April 2004.

## 4. Results

Any river describes a trajectory. Upstream events impact downstream functioning. Downstream services require upstream management, as for navigation or contamination, for instance. A river and its nested riverine SESs thus form a perfect object for a general study on SES trajectories.

Located on the Upper Rhine River, in the south of the Strasbourg city, the Rohrschollen island is one of these areas that were significantly affected by the Upper Rhine river projects for flood mitigation, navigation, harbor development, hydropower production, as well as by French-German relationships.

We focus on the management of water bodies : the Upper Rhine river between Basel (Switzerland) and Lauterbourg (France), the Rhenan aquifer and the smaller ones within the Rohrschollen area (Old Rhine, port basins, Bauerngrundwasser stream). The Rhenan alluvial forest ecosystem they support is also of interest. Maps indicating some particular points (yellow for HPP, red for risk/crisis, magenta for Port extensions) are plotted in Fig. 4. The background picture is a Normalized Difference Vegetation Index (NDVI) raster at a resolution of  $0.05^\circ$  (EPSG :4326, MODIS product downloaded from USGS). The raster from April 2004 was chosen for a reasonable contrast.

Some long term observations and indicators are reported in subsection 4.1. The timeline construction and a temporal analysis are presented in subsection 4.2. These are discussed in section 5 from a multi-scale point of view.

### 4.1. Indicators

Spatio-temporal data on governance, management, population, biodiversity and climate, are essential to

construct the trajectory of a SES, but they are not sufficient to the analysis when Human-Nature interactions are neglected.

This subsection provides thematic qualitative information together with some quantitative indicators on five components of the SES. Some interactions are pointed out.

#### 4.1.1. Governance tipping points

The Upper Rhine has been is a natural border between France and Germany and their precursors since a long time. It was conquered repeatedly by one side or the other. In the early 19th century, the main issues were floods and the induced river/border shifts, navigation come next.

The Napoleonic war period fostered their solution. Firstly, two agreements were reached on the free navigation : the "Convention de l'octroi" (1804) and the Convention of Vienna (1815). The latter created the Central Commission for the Navigation on the Rhine (CCNR, (Doerflinger, 1987)), an international organization still active to this day. The Rhine became an international river. Secondly, the Rhine river and the frontier were fixed by the Tulla's straightening project, mitigating the flood risks and improving the navigation in the Upper Rhine valley for a while (see subsection 4.2).

After World War I, France obtained the exclusive right to develop the Upper Rhine river by the contentious Treaty of Versailles (1919). With the agreement of the CCNR, the Grand Canal of Alsace (GCA) is dug parallel to the Upper Rhine river to facilitate the navigation towards Switzerland by setting up four locks and four hydropower plants (HPP) (Tricart and Bravard, 1991). This created the longest "Rhine island", downstream of Kembs HPP. After World War II, French-German relationships improved, resulting in the creation of the European Coal and Steel Community (ECSC) (Henze, 2005) and the further European construction.

The evolution of the French-German relations may be observed in the HPPs projects set up along the Upper Rhine river. Upstream, the GCA alimentes the 4 oldest HPP. With regards to German concerns about dewatering, the next 3 were implemented by means of 3 smaller derivation channels creating smaller islands (notably the Rohrschollen island). These are operated by France only. The last two HPP are implemented in line and co-operated by the two countries. France also authorizes two agriculture and HPP dams on the Old Rhine River (Breisach, and Kehl within the Rohrschollen area).

The Rohrschollen area provides an illustration of co-management. The island creation lowered the water table (subsection 4.1.3) and dried farmlands loca-

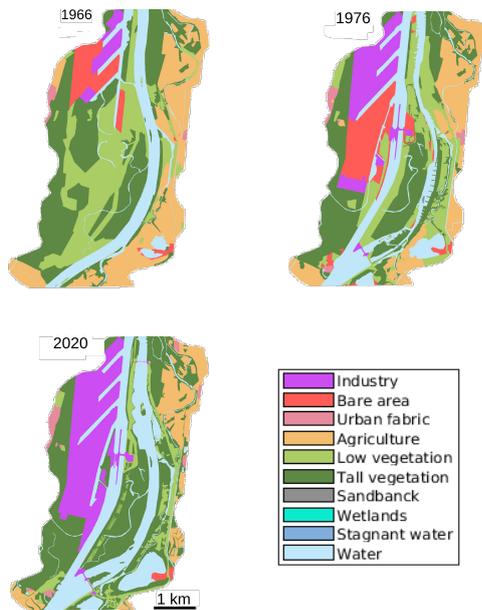


FIGURE 5 – Land cover/land use in 1966, 1976 and 2020.

ted on the German riverside. An agreement was reached in 1982 about the construction and the management of the Kehl's agriculture dam by the German authorities, as well as a mitigation plan for the mitigation of the downstream flood risk (subsection 4.1.5). It was activated in 2013 and 2021 by locking Kehl's dam and submersing the flood retention area of the Rohrschollen island.

From 1997, the National Natural Reserve status imposes new management rules on the Rohrschollen island (subsections 4.1.4 and 4.2.5).

#### 4.1.2. Land cover tipping points

In a floodplain, land cover and land use are intimately linked to the type of the river and the management actions.

As discussed in (Tricart and Bravard, 1991), historical maps show how the Rhine river was turned from a braided river to a rather straight channel following Tulla's project. For the Rohrschollen island, maps were geo-referenced, polygonized and clipped by extent (Eschbach et al., 2018).

The aerial and satellite pictures taken in 1966, 1976 and 2020 are of particular interest since they monitor the industrial development of the Autonomous Port of Strasbourg (PAS) in the Rohrschollen zone. These pictures were downloaded from the web portal "Remonter le temps" (IGN), then processed, see Fig. 5.

The sinuosity indicator is a by-product of the land cover maps. In a flat flood plain, this indicator may be es-

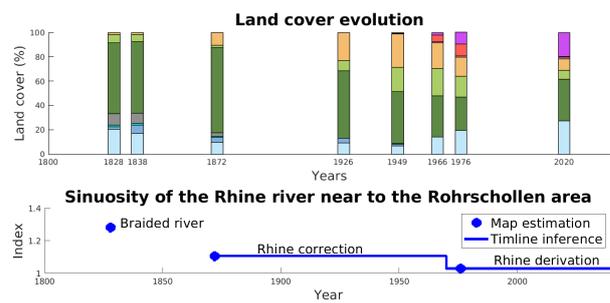


FIGURE 6 – Land cover and sinuosity evolution in the Rohrschollen area of Fig. 6.

timated as the reach length over the distance between its inflow and outflow points. The land cover and sinuosity evolution are plotted in Fig. 6 against some of the engineering actions (correction, derivation). The line break of 1970 corresponds to the island creation. Lower the sinuosity, faster the stream flow. Some impacts of the channelizations on the ecosystems are discussed in subsections 4.2.3 and 4.2.4. The reader is referred to (Arnaud et al., 2019) for an exhaustive description of the engineering impacts on the Upper Rhine floodplain over the two last centuries.

The land cover maps of (Eschbach et al., 2018) and Fig. 6 indicate that the island creation results from an anthropic management plan. However, the local toponymy – Bauerngrundinsel (agricultural island), Bauerngrundwasser (agricultural land water), Rohrschollen kopf (that may be translated as reed land terrace) – assesses that parts of the Rohrschollen island preexisted and were used for agriculture. Upstream of Strasbourg, this area was then a relevant place for an HPP project.

#### 4.1.3. Groundwater

The Rhenan aquifer is one of the largest groundwater reserves in Europe, representing 35 billions m<sup>3</sup> for the Alsatian part. Its supply is ensured by precipitations in the floodplain, by infiltration from the Vosgian and Black Forest streams and the Rhine river.

The aquifer serves freshwater (Plobsheim's water intake, upstream Strasbourg), water sourced heat, industry (including breweries) and agriculture. Irrigation puts pressure on the groundwater as noted by the observatory Aprona. More generally, anthropic activities have impact in terms of quantities and contamination (Bernhard et al., 1992). An evaluation of the total economic value of the Alsatian aquifer is proposed in (Masson et al., 2000).

Some piezometric time series measured from 1971 to 2001 in the Neuhof forest were downloaded from the

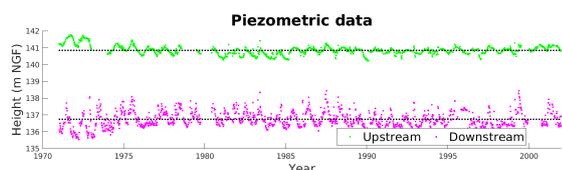


FIGURE 7 – Piezometric data at “Fort Hoche” (upstream) and “Forêt du Neuhof” (downstream) stations.

Aprona databasis to comment on the local impact of the island creation onto the aquifer, the alluvial forest and the agriculture. These are plotted in Fig. 7 for the upstream (Fort Hoche) and downstream (Forêt du Neuhof) stations.

As discussed for previous HPP and lock structures (Tricart and Bravard, 1991), the 1970 channelization impacted the water table height. Upstream, the creation of the island drained the aquifer. The agricultural dam on the Old Rhine river in 1985 was set up as a mitigation measure. Downstream, the new channel and the port basins raised the water table.

The very short aquifer temperature time series (measured from 2017 onward at PAS station) exhibits an upward trend in agreement with the recent heat waves and the climate change, see subsection 4.1.5.

#### 4.1.4. Life

As quoted in (Denis, 2009), “the” primitive (alluvial) Rhenan forest no longer exists : one should rather speak of “the” Rhenan forests as a succession of forest massifs of a few hundred hectares each. One considers as such all afforestation included in the former major bed of the river. The difference in the forests stands (softwood, 3 stages, hardwood) is a relevant indicator to evaluate the alluvial status of the Rhenan forests (Eschbach et al., 2018).

The human population curves for the cities of Strasbourg and Kehl, Fig. 8, are plotted using a logarithmic scale. These confirm the differences in the urbanization and industrial developments on the French and German sides as already noticed in subsection 4.1.2. These curves raise two comments. Firstly, the minima in the Strasbourg curve are explained by wars’ impacts in the “Alsace-Lorraine” land (volunteer emigration, organized immigration, evacuations and expulsions). Secondly, the German industries and their worker population mainly grew in the Ruhr area, within the Lower Rhine basin. Besides, the Rohrschollen area/island has always been an uninhabited one.

The National Natural Reserve (RNN) status (Eurométropole de Strasbourg, 2018a) has fostered the know-

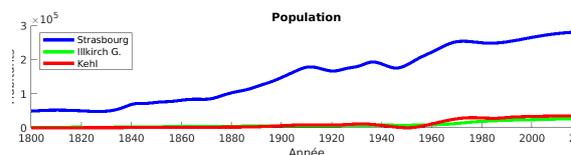


FIGURE 8 – Evolution of Strasbourg and Kehl populations.

ledge on the island fauna and flora populations. Inventories, see (Trieber, 2021) for instance, that were conducted since 1970 by a number of naturalistic associations were used in the scientific study joined to the RNN status demand. The RNN management documents (Eurométropole de Strasbourg, 2018a), scientific papers and inventories describe pressures exerted upon the alluvial ecosystem.

The RNN status also defines the authorized Human-Nature interactions. Visits to the island increased from 31875 people in 2013 to 40 160 people in 2017, including scholars, hikers, scientists and managers. Counts are facilitated by the limited number of three pedestrian accesses. Ecological responsibility is instructed through panels (information, interpretation, direction, rules). Authorized practices are fruit and mushroom picking, fishing, cycling and hiking on pathways, while prohibited activities are camping, forestry, hunting, sporting and water related activities (Eurométropole de Strasbourg, 2018a, p. 7).

#### 4.1.5. Risks

Risks evolve together with engineering plans, industrialization and climate change.

Before 1850, floods as well as induced the river and border shifts represented the major risks for the farmers and the riverine population, for their lives and their activities (Tricart and Bravard, 1991). At that time, endemic malaria was also an issue. The channelization and the resulting erosion fixed the river bed and the French-German border. Malaria disappeared in 1885 (Callot, 1948) as in the other parts of France. Unfortunately, the erosion was higher than expected, impacting the bathymetry and the navigation along the Upper Rhine river. For more detail, flood events are reconstructed in (Himmelsbach et al., 2015; Martin, Brice et al., 2015).

In 1986, near to Basel, the Sandoz factory of Schweizerhalle (Switzerland) burned, resulting in a spill of 20 tonnes of agrochemicals. A 70 km red trail ran downstream the Rhine river and killed fishes over a distance of 400 km. The Rhine was declared “dead”. This affected the aquifer too (Schwabach, 1989), including Plobsheim’s freshwater intake. Twenty years of decontamination were necessary to restore the ecological balance

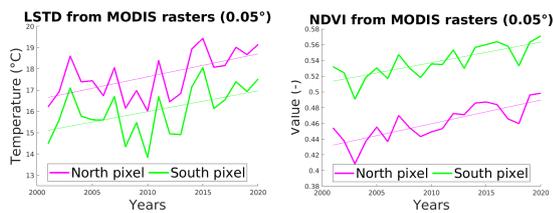


FIGURE 9 – LSTD and NDVI yearly means for the north and south parts of the Rohrschollen area.

after the so-called “Tchernobâle” event. This major industrial accident contributed to the set up of new rules.

Initially located in Strasbourg, the PAS has nowadays extensions over 100 km. It hosts a number of Seveso sites within its oil port (1927) downstream of the Rohrschollen area.

Climate change is noticeable on daily air temperature (see the long term data from Strasbourg Entzheim airport (Klein Tank et al., 2002)), land surface temperature (LST Day from MODIS rasters), aquifer temperature (Aprona data at PAS station), with impacts on fauna and vegetation. As the Rohrschollen island lies in two pixels of the MODIS 0.05° grid, monthly rasters may be used to evaluate yearly means for LSTD and NDVI. As displayed in Fig 9, computed indicators present the same growing trend. As expected, values differ. The RNN forested part (south pixel) is much cooler (-1.6 °C) and greener than the port area (north pixel), and brings regulation ecosystem services. The increase in the temperatures contributes to the eutrophication of the Bauerngrundwasser stream.

Besides, the climate change has also favored the establishment and the spread of the so-called “tiger mosquito” (*Aedes albopictus*) population in the Eurometropolis of Strasbourg (see the animated map from the mosquito control union), increasing the zoonosis risk (dengue fever, chikungunya and zika).

The impacts of climate change on the navigation of the Rhine are discussed on the CCNR website

#### 4.2. Timeline chart

A number of chronologies already report on the development of Rhine (Doerflinger, 1987; Tricart and Bravard, 1991; Frijters and Leentvaar, 2003; Uehlinger et al., 2009; Alsace Nature, 2010), historical floods (Himmelsbach et al., 2015) and flood prevention services (Préfet coordonnateur de bassin Rhin-Meuse, 2012), the development of the port and the city (Ahnne, 1958; Bonnet et al., 2016), islands and RNN creations (Eurométropole de Strasbourg, 2018a), addressing different spatial and temporal scales (Elissalde, 2000).

Consequently, this paper is not about a question of finding new data, but a matter of organizing and analyzing heterogeneous data.

We compile this information in a spreadsheet (available from the Indores web portal) (Charpentier, 2023) to draw the timeline and to analyze the evolution of the Upper Rhine river between Basel and Lauterbourg (France), the Rohrschollen area, and the nested SES they form.

##### 4.2.1. Timeline template

For this case study, we use three classes representing the international level, the Upper Rhine level and the Rohrschollen level, respectively. For each class, we use some of the conceptual scheme components (Fig. 1) to distinguish external drivers, actors and processes representing the social template, the adaptive management interface, and the “Stocks→Ecosystem services” subclass that represent the biogeophysical template and the services it provides. Conventions, regulations or events at a given level are external drivers for the lower levels.

The Upper Rhine/Rohrschollen timeline information is encoded in a spreadsheet containing about 150 rows that represent about 130 actual data and 20 classification comments. This is interpreted using the ZATimeline software to plot Fig. 10. Longitude and latitude columns are added to the spreadsheet. These were used to plot Fig. 4.

The legend is encoded in another spreadsheet and plotted in a second figure using ZATimeline. Long rectangles and triangles indicate periods, positive or negative trends. Symbols are used for events : □ for a convention, △ for a setup, ○ for another event. Colors distinguish themes : magenta for navigation, blue for the river and the aquifer, green for ecology, yellow for dams (HPP and/or agriculture), orange for society, and red for crisis and risks. The texts written in gray and white rectangles are comments related to classes and sub-classes.

The timeline together with indicators allow for a different kind of analysis. The chronology is recalled in this subsection. The first two phases are dedicated to the Rhine river channelization process. The last two phases focus on the Rohrschollen development. In that sense, the narrative agrees with the shrinking process of both the river bed and the alluvial forest.

Complementary views, panarchy and local gear, are discussed in subsections 5.2 and 5.3, respectively.

##### 4.2.2. Threads and divagations

Flowing in the Upper Rhine graben, the Rhine river was a braided one up to the middle of the 19<sup>th</sup>, shifting

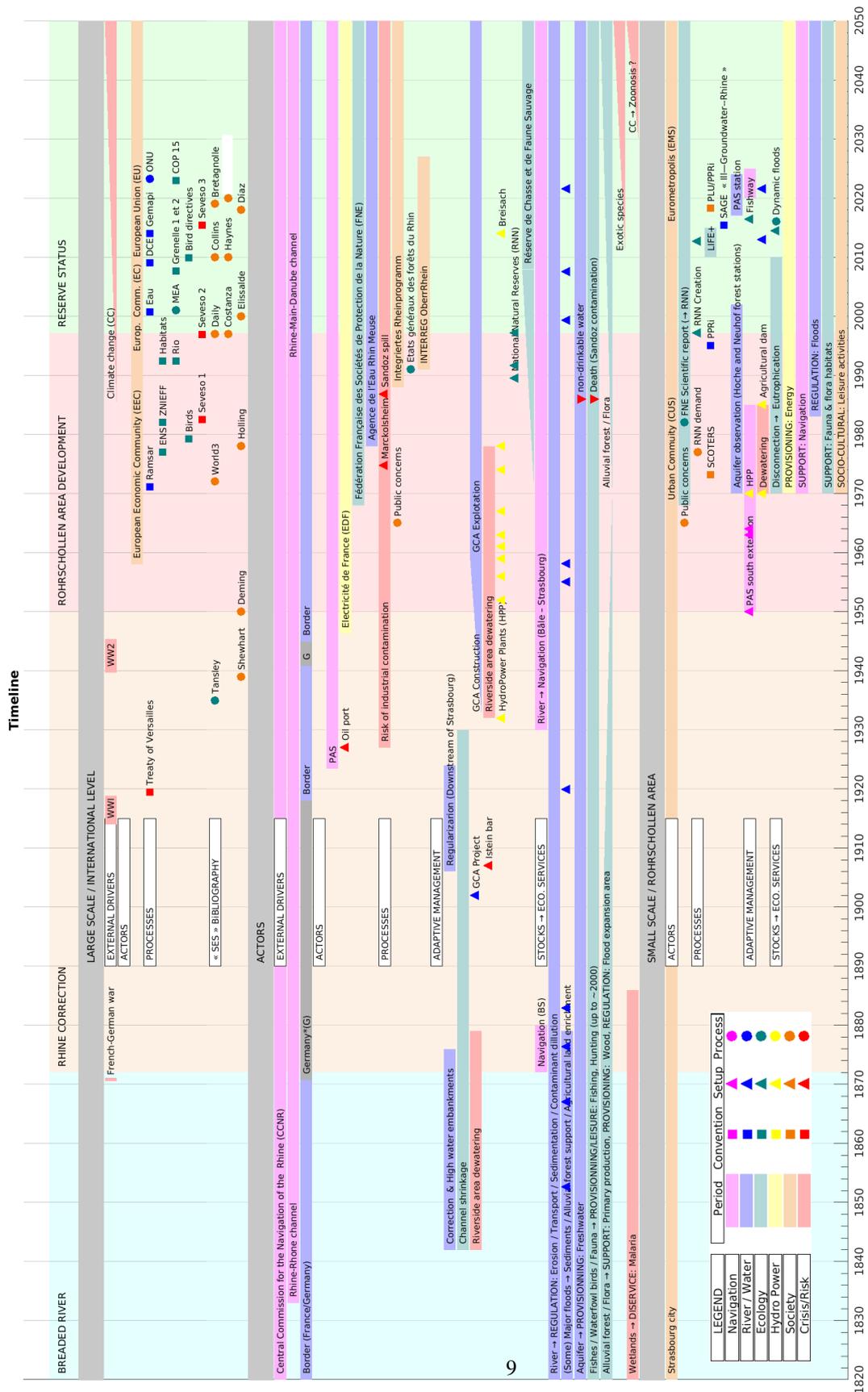


FIGURE 10 – Upper Rhine/Rohrschollen multi-scale social ecological timeline created from the spreadsheet and the ZATimeline GUI. The legend (created with ZATimeline too) is added afterwards.

with the floods, creating and removing islands, opening space to the development of the alluvial (soft wood) forest, offering a biologically rich environment, and bringing sediments to agricultural lands. This can be considered as the initial/natural state of the Upper Rhine river trajectory.

Navigation was dangerous downstream of Strasbourg and impossible between Basel and Strasbourg. Floods endangered neighboring populations (Himmelsbach et al., 2015), even the population set up some local provisional barriers intended as mitigation measures (Tricart and Bravard, 1991). The border between the precursors of France and Germany was following the river moves, impacting property rights.

In the early 19<sup>th</sup> century, the rise of empires led to the "Convention de l'octroi" (1804) between the French Empire and the Holy Roman German Empire that imposed a unified toll system for the navigation of the Rhine. Eleven years later, the Vienna conference created the CCNR (Doerflinger, 1987). It became an international river.

#### 4.2.3. Rhine correction

Several engineering projects were proposed to alleviate the flood risks along the Rhine river (Tricart and Bravard, 1991). Tulla's project was implemented from 1840 to 1879. Small shallow channels were hand dug in meanders, reducing the length of the Upper Rhine river, and speeding up the flow. The faster stream flow flushed sediments, shrunk and sunk the river bed.

After works, the Upper Rhine river and its major bed drastically changed their appearance. Riverside lands were drained lowering the water table and impacting agriculture (Tricart and Bravard, 1991; Arnaud et al., 2019). This alleviated the flood risk locally, but increased it in the Middle and Lower Rhine areas. As in the other parts of France, malaria disappeared (Callot, 1948) by 1885.

The Neuhof forest and the Rohrschollen area constituted a unique forest system run by a number of small streams for more than one century. As on the Upper Rhine riversides, forest stands changed from Rhenan alluvial ones (3 stages) to hardwood stands. The river incision facilitated the navigation between Basel and Strasbourg (Zimmermann, 1905) up to the discovery of the Istein bar (Unknown, 1931). Downstream, eroded sediments were continuously impacting the bathymetry, placing constraints on the navigation.

Represented on the timeline by a change of phase, the correction constitutes the major tipping point in the social ecological trajectory of the Upper Rhine river and its ecosystems.

From 1871 to 1918, the Upper Rhine river was flowing in Germany. The regulation was decided and funded by the German authorities in 1905 to facilitate the trading navigation between Strasbourg and Germerheim.

After World War I and the Treaty of Versailles (1919), the French Grand Canal of Alsace (GCA) reestablished the navigation of the Rhine between Basel and Strasbourg through the co-location of HPPs and locks on the channel. We do not consider it as a social ecological tipping point since it did not impact ecosystems as the Rhine correction did.

Funded in 1923, the PAS is co-managed by the Strasbourg city and the French state.

#### 4.2.4. Development

Industrial development, global trade and energy needs have greatly accelerated (Meadows et al., 1972; Steffen et al., 2015) after World War 2. At the same time, a general ecological awareness grew in the public and the scientific community (Meadows et al., 1972; Westman, 1977; Holling, 1978) at all scales, fostering political conventions and regulations.

These apply to the PAS. In the Rohrschollen area, the PAS extension became visible around 1950 (see Fig. 6). A derivation channel dedicated to the navigation (lock) and to the hydropower production (HPP) is dug in the sixties under the agreement of the CCNR. It separated the Rohrschollen island from the Neuhof forest. It also disconnected the Bauerngrundwasser stream from the Rhine river. several port basins were created downstream of the HPP.

This industrial development grabbed natural space. The new drainage system contributed to lower the water table upstream and, conversely, to raise it downstream. This dewatering was an issue for both the German farmers and the forest ecosystem. Following a German demand, Kehl's agriculture dam built on the Old Rhine river in 1985 stopped the dewatering of the soil (see Fig. 7). The aquifer heights progressively returned to previous states. In that sense, the Kehl's dam may be considered as the first renaturation operation.

Concurrently, in 1975, after the occupation of the site by French and German ecologists, a PAS extension intended in Marckolsheim was rejected by the administrative court (Prieur, 1976) on the basis of the decrease in surface and the ecological status of the Rhenan alluvial forest. A few years later, the city of Strasbourg entrusted a regional federation of naturalist associations (today France Nature Environment) with a scientific study about the island ecosystem. This was enclosed with the

demand of the RNN status for the island (Eurométropole de Strasbourg, 2018a). In the timeline, the end of the development phase coincides with the RNN status for the Rohrschollen island.

#### 4.2.5. Preservation

The biogeophysical restoration of rivers impacted by anthropic activities is a scientific concern that emerged in the 1990s (Aelbrecht et al., 2010). In the Upper Rhine region, a number of joint French-German-Swiss initiatives are dedicated to the Rhenan alluvial forests. These raised awareness, then facilitated funding. Financial resources come from INTERREG projects, supplemented by a number of local or regional agencies, as well as from compensation measures (Alsace Nature, 2010).

The Rohrschollen area is the result of a long series of changes. The remains of the “alluvial forest” part of the island is proclaimed a RNN in 1997 after a process of 20 years, and more than thirty five years after its separation from the Neuhof sub-natural forest (Fig. 6). The Neuhof forested massif become a RNN in 2012. In a very small nutshell, natural reserves are managed through regulation, ecological studies and objectives such as ecological awareness, educational activities or restoration, see (Eurométropole de Strasbourg, 2018a) for instance.

On the island, sufficient flooding is a key requirement to restore, then to maintain an alluvial forest disconnected from the channelized Rhine river since 1870, and disconnected from the new channel since 1970.

On the one hand, the implementation of a civil engineering structure between the channel and the Bauerngrundwasser was conducted under a LIFE+ project (Eschbach et al., 2018). It was operated twice in 2014 and 2016 for dynamical flooding. On the other hand, the Rohrschollen island (in collaboration with German authorities that control the Kehl’s dam) as well as the Erstein and Moder polders may be mobilized as flood retention zones (Préfet du Bas-Rhin, 2018). This was the case in 2013 and for the latest paramount Rhine flood of 2021. Note that flow dynamics are different.

The restoration objectives of the LIFE+ project was “6 to 8 dynamic floods a year”. Ten years later, the achievement of this flooding objective is still a hot topic for the management of the RNN (Eurométropole de Strasbourg, 2018b, p. 18). The actual setup of recurrent dynamical floods will constitute a tipping point for the Rohrschollen ecosystem. Locally, the naturalness of the alluvial forest is on engineering support.

Smaller but relevant initiatives also include a fishway (2019) installed in the derivation channel by EDF, and five Highland cattle cows (2021) to graze Rohrschollen wet meadows, ensuring a lower impact than mo-

wing onto fauna and flora and a higher efficiency in wet conditions.

## 5. Discussion

The trajectories and adaptive management are discussed on the basis of the timeline and the frameworks presented in subsection 2.

### 5.1. Adaptive wheel

The key difference in the conceptual schemes (Collins et al., 2010; Haines-Young and Potschin, 2010; Bretnolle et al., 2019) and the adaptive wheel (Shewhart, 1939; Deming, 1982) is in the dynamics. On the one hand, conceptual schemes describe a feedback loop without considering the time variable in an explicit manner. A conceptual scheme may be drawn for each of the four phases identified on the timeline. On the other hand, the adaptive wheel (PDCA) advances in time describing the trajectory of Fig. 2 in a continuous manner.

The adaptive wheel agrees to the river management plans carried out along time. The present tense is used to express the continuity of the process. A simplified sequence may be :

- (Plan 1) Tulla’s correction for flood mitigation and navigation, (Do 1) excavation (1879), (Check 1) upstream erosion and downstream sedimentation interfere the navigation, (1905) (Act 1) define new management plans,
  - Upstream : (Plan 2a) project of the Grand Canal of Alsace (1902), (Do 2a) excavation from 1932 to 1959 (4 HPPs), (Check 3) dewatering, (Act 3) next 3 HPPs are isolated ones,
  - Downstream : (Plan 2b) regularization, (DO 2b) set barriers and groynes in the river bed (Tricart and Bravard, 1991), (Check 2b) Satisfaction,
- (Plan 3) consolidate French-German relationships, (Do 3) 2 co-operated HPPs, (Check 3) Satisfaction,
- (Plan 4) restoration of Rohrschollen island, (Do 4) Set up a water intake and run dynamical floods, (Check 4) operated twice with preliminary satisfactory results in 2016 (Eschbach et al., 2018), (Act 4) reiterate the operation (long wait) (Eurométropole de Strasbourg, 2018a),
- (Plan 6) mitigation of the climate change effects...

Occasionally, the SES may enter in a crisis (Holling, 1978), loosing stability as in Fig. 3. This is the case for the Rhenan alluvial forests, the preservation of which is finally a recent ecological concern.

### 5.2. Panarchy view

The panarchy model (Holling, 1978) was proposed to work on nested systems, their interactions, their co-evolutions and their transformation. Nested geographical areas and their SESs are thus good candidates for a panarchy analysis. The timeline template described in subsection 4.2.1 and applied in Fig. 10 allows for such analyses.

As an example of top down interactions, the international conventions and European regulations about ecology are translated and funded at the lower scales within some delay. The correction and erosion upstream of Strasbourg, the sediment of which impacted the navigation of the Rhine river may be regarded as a bottom up interaction.

The adaptive cycle assumes a crisis. The Sandoz spill (1986) (Schwabach, 1989) had impacts at the three scales : the contamination at the lower scales (punctual crisis, contaminant transport, social ecological impacts) and the strengthening of rules at the international level (adaptive management). More generally, risks described in subsection 4.1 are sources of potential crises

The extreme event of July 2021 is an example where the local flood retention zones contributed to mitigate the flood crest in the Middle and Lower Rhine basins. The adaptive management and flood mitigation plans written at the different scales are designed to solve known issues. Hopefully, the general functioning of nested SESs may be represented as a gear of difference sized, adaptive cycles (Deming, 1982), while the Holling's panarchy model agrees with crises.

Climate change is a significant concern that can be observed not only in the temperature increase, but also in the bloom of mitigation strategies implemented at various levels, (Goergen et al., 2010; Agence de l'Eau Rhin-Meuse, 2018) for instance.

### 5.3. Local gear

The Rohrschollen area comprises three contrasted SESs. From west to east, these are the industrial PAS part (and a piece of the Neuhof Forest RNN), the Rohrschollen island, and the agricultural German area. The evolution of their land use and land cover, Fig. 6, illustrates the difference in their trajectory. Historical reasons for their divergent trajectories are already discussed in subsections 4.1.1.

Conceptual schemes and/or adaptive wheels may be drawn for each of these three SESs. The point is then to observe how they interact into a local gear.

Underground, the Rhenan aquifer serves agriculture and trees. The impact of the derivation (1970) and of

Kehl's agriculture dam on the water table heights are observable in the piezometric data (Fig. 7). Clearly, the management of the two locks contribute to maintain the ecosystem services provided by the aquifer.

At the ground level, the island is accessible from the HPP road, the cycle track over the south dam, and a road over Kehl's dam. Since the Bauerngrundwasser stream is disconnected from the Rhine, any floods that occur on the island are managed, regardless whether they are dynamical or not. Accesses are closed accordingly.

Water management is obviously the key concern between the three systems, even if expected services are different : navigation and hydro-power production for PAS, support to fauna and flora habitats on the island, and irrigation for agriculture. Three flood retention area has a value for downstream SESs. As said in subsection 4.2.5, the sustainability of the island naturalness is on engineering support.

Some interviews of the managers of these three ecosystems as well as more information about the German side would be precious to go one step further in the analysis of the social ecological interactions. In that case, the timeline could be a relevant mediation tool to animate the discussion and to compile new information.

## 6. Conclusion

Information was selected in the rich scientific and gray documentation written about the Upper Rhine river development. This was organized by means of the ZATimeline software. The various analyses conducted with regards to social ecological schemes and adaptive management cycles emphasize the importance of the continuous water management for the sustainability of the desired ecosystem services. These were mainly flood mitigation and navigation for a long time. The rise of ecological concerns about the Rhenan alluvial forest were recently translated into the RNN status and an engineering support.

The ZATimeline software is shown to be effective in a number of social ecological studies carried out in the Réseau des Zones Ateliers . Its real-time plotting abilities allow to use it as a mediation tool during workshops. A collaborative design of a CHRONO-RHINE website based on the CHRONO-RHONE (Arnaud, 2019) approach could be of interest to go one step beyond in the collection of biodiversity data and in the representation of the Upper Rhine SESs.

## Références

- Aelbrecht, D., Béal, D., Piégay, H., 2010. Restauration morphodynamique et redynamisation de la section court-circuitée du Rhin à l'aval du barrage de Kembs (projets interreg / edf), in : 32èmes Journées de l'Hydraulique de la Société Hydrotechnique de France Environnement et Hydroélectricité Lyon - 6 et 7 octobre 2010. 2010., pp. 53–60. URL : [https://www.persee.fr/doc/jhydr\\_0000-0001\\_2010\\_act\\_32\\_1\\_1162](https://www.persee.fr/doc/jhydr_0000-0001_2010_act_32_1_1162).
- Agence de l'Eau Rhin-Meuse, 2018. Le plan d'adaptation et d'atténuation au changement climatique. URL : [https://www.eau-rhin-meuse.fr/sites/default/files/2021-09/18\\_03\\_01\\_brochure\\_aeRM\\_BD.pdf](https://www.eau-rhin-meuse.fr/sites/default/files/2021-09/18_03_01_brochure_aeRM_BD.pdf).
- Ahnne, P., 1958. Strasbourg 1850-1950 : métamorphoses et développement. Dernière nouvelles de Strasbourg. URL : <http://catalogue.bnf.fr/ark:/12148/cb328992358>.
- Alignier, A., Bergerot, B., Houet, T., Langlais-Hesse, A., Nabucet, J., Viaud, V., 2020. Trajectoires des systèmes bocagers du nord de la zone atelier armorique : approche chrono-systémique des déterminants de la relation de l'homme à la haie. 5ème colloque des Zones Ateliers, [sciencesconf.org/20ans-rza](https://sciencesconf.org/20ans-rza):329872. Accessed : 2022-11-23.
- Alsace Nature, 2010. Proposition des associations de la protection de la nature pour la sauvegarde du Rhin et des forêts Rhénanes. URL : <https://alsacenature.org/wp-content/uploads/2022/02/AN-2010-Biodiv-propositions-rhin-web.pdf>.
- Arnaud, F., 2019. CHRONO-RHÔNE : Elaboration d'une frise chrono-systémique pour l'OHM Vallée du Rhône, in : Séminaire scientifique annuel de l'OHM Vallée du Rhône, GRAIE, Villeurbanne, France. p. 1. URL : <https://hal.archives-ouvertes.fr/hal-02140681>.
- Arnaud, F., Charpentier, I., Chery, J.P., Gradeler, M., Bonnal, V., Dunesme, S., 2022. Potentialités des frises chrono-systémiques et des cartographies narratives pour communiquer sur les trajectoires des socio-écosystèmes, in : Journées Prospectives INEE, La Rochelle, France. p. 1. URL : <https://hal.archives-ouvertes.fr/hal-03828948>.
- Arnaud, F., Schmitt, L., Johnstone, K., Rollet, A.J., Piégay, H., 2019. Engineering impacts on the upper rhine channel and floodplain over two centuries. *Geomorphology* 330, 13–27. URL : <https://www.sciencedirect.com/science/article/pii/S0169555X19300042>, doi : <https://doi.org/10.1016/j.geomorph.2019.01.004>.
- Bergeret, A., George-Marcelpoil, E., Delannoy, J.J., Piazza-Morel, D., 2015. L'outil-frise : une expérimentation interdisciplinaire. Technical Report. les Carnets du Labex ITEM. URL : <https://hal.archives-ouvertes.fr/hal-01230027>.
- Bernhard, C., Carbiener, R., Cloots, A., Froehlicher, R., Schenck, C., Zilliox, L., 1992. Nitrate pollution of groundwater in the alsatian plain (france)—a multidisciplinary study of an agricultural area : The central ried of the ill river. *Environmental Geology and Water Sciences* 20, 125–137. doi : [10.1007/BF01737879](https://doi.org/10.1007/BF01737879).
- Bonnet, D., Kovar, J.F., Zvardon, F., 2016. Un port au coeur de la ville ; le port autonome de Strasbourg. Editions du Signe.
- Bretagnolle, V., Benoit, M., Bonnefond, M., Breton, V., Church, J.M., Gaba, S., Gilbert, D., Gillet, F., Glatron, S., Guerbois, C., Lamouroux, N., Lebouvier, M., Mazé, C., Mouchel, J.M., Ouin, A., Pays, O., Piscart, C., Ragueneau, O., Servain, S., Spiegelberger, T., Fritz, H., 2019. Action-orientated research and framework : insights from the french long-term social-ecological research network. *Ecol. Soc.* 24, 10. doi : [10.5751/ES-10989-240310](https://doi.org/10.5751/ES-10989-240310).
- Bruley, E., Locatelli, B., Vendel, F., Bergeret, A., Elleaume, N., Grosinger, J., Lavorel, S., 2021. Historical reconfigurations of a social-ecological system adapting to economic, policy and climate changes in the french alps. *Reg. Environ. Change* 21, 34. doi : [10.1007/s10113-021-01760-8](https://doi.org/10.1007/s10113-021-01760-8).
- Callot, J., 1948. Le paludisme en Alsace et en Moselle à propos d'une enquête récente. *Annales de parasitologie humaine et comparée* 23, 289–295. doi : [10.1051/parasite/1948235289](https://doi.org/10.1051/parasite/1948235289).
- Charpentier, I., 2020. Zatimeline : User guide v1.0. URL : <https://hal.science/hal-04059839>.
- Charpentier, I., 2023. Timeline data for the social-ecological system of the Upper Rhine/Rohrschollen case study. data.InDoRES, V1. doi : [10.48579/PRO/BHG8JR](https://doi.org/10.48579/PRO/BHG8JR). accessed : 2023-04/25.
- Cognard, V., Baltzinger, C., Robert, A., Servain, S., 2020. Gouvernance et changements de trajectoire au sein du domaine national de chambord : un territoire emmuré depuis 5 siècles. 5ème colloque des Zones Ateliers, [sciencesconf.org/20ans-rza](https://sciencesconf.org/20ans-rza):329805. Accessed : 2022-11-23.
- Collins, S.L., Carpenter, S.R., Swinton, S.M., Orenstein, D.E., Childers, D.L., Gragson, T.L., Grimm, N.B., Grove, J.M., Harlan, S.L., Kaye, J.P., Knapp, A.K., Kofinas, G.P., Magnuson, J.J., McDowell, W.H., Melack, J.M., Ogden, L.A., Robertson, G.P., Smith, M.D., Whitmer, A.C., 2010. An integrated conceptual framework for long-term social-ecological research. *Front. Ecol. Environ.* 9, 351–357. doi : [10.1890/100068](https://doi.org/10.1890/100068).
- Costanza, R., d'Arge, R., de Groot, R.e.a., 1997. The value of the world's ecosystem services and natural capital. *Nature* , 253–260doi : [10.1038/387253a0](https://doi.org/10.1038/387253a0).
- Daily, G., 1997. Introduction : What are ecosystem services?, in : *Nature's Services : Societal Dependence on Natural Ecosystems*. Island Press, Washington DC, pp. 1–10.
- Davies, K.K., Fisher, K.T., Dickson, M.E., Thrush, S.F., Heron, R.L., 2015. Improving ecosystem service frameworks to address wicked problems. *Ecol. Soc.* 20. doi : [10.5751/ES-07581-200237](https://doi.org/10.5751/ES-07581-200237).
- Deming, W.E., 1982. *Out of the crisis*. Cambridge, Mass.
- Denis, P., 2009. L'avifaune nicheuse des forêts rhénanes alsaciennes : Relation avec le milieu et mise en perspective géographique et historique. URL : <http://www.crdp-strasbourg.fr/data/patrimoine-nature1/foret/documents/memoire.pdf>. mémoire de Master, Ecole Pratique des Hautes Etudes (Accessed 2023-05-11).
- Doerflinger, R., 1987. La commission centrale pour la navigation du Rhin : 170 ans d'évolution du statut international du Rhin. URL : [https://www.ccr-zkr.org/files/histoireCCNR/07\\_ccnr-170-ans-evolution-statut-international-du-rhin.pdf](https://www.ccr-zkr.org/files/histoireCCNR/07_ccnr-170-ans-evolution-statut-international-du-rhin.pdf).
- Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., Hill, R., Chan, K.M.A., Baste, I.A., Brauman, K.A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P.W., van Oudenhoven, A.P.E., van der Plaats, F., Schröter, M., Lavorel, S., Aumeeruddy-Thomas, Y., Bukvareva, E., Davies, K., Demissew, S., Erpul, G., Failler, P., Guerra, C.A., Hewitt, C.L., Keune, H., Lindley, S., Shirayama, Y., 2018. Assessing nature's contributions to people. *Science* 359, 270–272. doi : [10.1126/science.aap8826](https://doi.org/10.1126/science.aap8826).
- Elissalde, B., 2000. Géographie, temps et changement spatial. *L'Espace géographique* 29, 224–236. doi : [10.3406/spgeo.2000.2008](https://doi.org/10.3406/spgeo.2000.2008).
- Eschbach, D., Schmitt, L., Imfeld, G., May, J.H., Payraudeau, S., Preusser, F., Trauerstein, M., Skupinski, G., 2018. Long-term temporal trajectories to enhance restoration efficiency and sustainability on large rivers : an interdisciplinary study. *Hydrology and Earth System Sciences* 22, 2717–2737. doi : [10.5194/hess-22-2717-2018](https://doi.org/10.5194/hess-22-2717-2018).
- Eurométropole de Strasbourg, 2018a. Réserve Naturelle Ile du Rohrschollen, Plan de gestion 2018-2022 Tome 1 – diagnostic. Technical Report. Eurométropole de Strasbourg. URL : <https://www.eurometropole-strasbourg.fr/ressources-et-services/le-patrimoine-naturel/la-reserve-naturelle-ile-du-rohrschoellen>.

- [/www.grand-est.developpement-durable.gouv.fr/IMG/pdf/2018\\_pg\\_roh\\_tome\\_01.pdf](http://www.grand-est.developpement-durable.gouv.fr/IMG/pdf/2018_pg_roh_tome_01.pdf).
- Eurométropole de Strasbourg, 2018b. Réserve Naturelle Ile du Rohrschollen, Plan de gestion 2018-2022 Tome 3 – fiches actions. Technical Report. Eurométropole de Strasbourg. URL : [https://www.grand-est.developpement-durable.gouv.fr/IMG/pdf/2018\\_pg\\_roh\\_tome\\_03.pdf](https://www.grand-est.developpement-durable.gouv.fr/IMG/pdf/2018_pg_roh_tome_03.pdf).
- Frijters, I., Leentvaar, J., 2003. Rhine case study. Technical Report. UNESCO. URL : <https://unesdoc.unesco.org/ark:/48223/pf0000133303>.
- Goergen, K., Beersma, J., Brahmmer, G., Buiteveld, H., Carambia, M., de Keizer, O., Krahe, P., Nilson, E., Lammersen, R., Perrin, C., Volken, D., 2010. Assessment of climate change impacts on discharge in the Rhine River Basin : Results of the RheinBlick2050 project. Technical Report. INRAE. URL : <https://hal.inrae.fr/hal-02594596>.
- Guerbois, C., Bellón, B., Blanco, J., Dervieux, Z., Nxumalo, B., Renaud, P.C., 2020. Evolution des contributions de la nature aux hommes dans le socio-écosystème de hwange : vers une construction transdisciplinaire de sa trajectoire. 5ème colloque des Zones Ateliers, sciencesconf.org:20ans-rza:329813. Accessed : 2022-11-23.
- Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem service and human well-being, in : *Ecosystem Ecology : A New Synthesis*. Cambridge University Press, pp. 110–139. doi :10.1017/CBO9780511750458.007.
- Henze, S., 2005. France, Germany and the struggle for the warming natural resources of the Rhineland . *ICE Case Studies* 158. URL : <https://mandalaproyects.com/ice/ice-cases/saar.htm>.
- Himmelsbach, I., Glaser, R., Schoenbein, J., Riemann, D., Martin, B., 2015. Reconstruction of flood events based on documentary data and transnational flood risk analysis of the Upper Rhine and its French and German tributaries since ad 1480. *Hydrol. Earth Syst. Sc.* 19, 4149–4164. doi :10.5194/hess-19-4149-2015.
- Holling, C., 1978. *Adaptive Environmental Management and Assessment*. John Wiley&Sons, Chichester.
- Klein Tank, A.M.G., Wijngaard, J.B., Können, G.P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Mauger, M., Leitass, A., Bukantis, A., Aberfeld, R., van Engelen, A.F.V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., Antonio López, J., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L.V., Petrovic, P., 2002. Daily dataset of 20th-century surface air temperature and precipitation series for the european climate assessment. *Int. J. Climatol.* 22, 1441–1453. doi :10.1002/joc.773.
- Lévêque, C., Pavé, A., Abbadie, L., Weill, A., Vivien, F., 2000. Les zones ateliers, des dispositifs pour la recherche sur l'environnement et les anthroposystèmes. *Natures Sciences Sociétés* 8, 44–52. doi :10.1016/S1240-1307(01)80005-4.
- Martin, Brice, Drescher, Axel, Fournier, Marie, Guerrouah, Ouarda, Giacona, Florie, Glaser, Rüdiger, Himmelsbach, Iso, Holleville, Nicolas, Riemann, Dirk, Schonbein, Johannes, Vitoux, Marie-Claire, With, Lauriane, 2015. Les événements extrêmes dans le fossé rhénan entre 1480 et 2012. quels apports pour la prévention des inondations ? *La Houille Blanche* 101, 82–93. doi :10.1051/lhb/20150023.
- Masson, S., Stenger, A., Verchère, A., 2000. Vers une évaluation de la valeur économique totale de la nappe phréatique d'Alsace. Technical Report. IRSTEA. URL : <https://hal.science/hal-00464083>.
- Meadows, D.H., Meadows, D.L., Randers, J., Behrens III, W.W., 1972. *The Limits to Growth. A Report for the Club of Rome's Project on the Predicament of Mankind*. Universe Books, New York.
- Moen, R.D., Norman, C., 2010. Clearing up myths about the deming cycle and seeing how it keeps evolving. *Qual. Prog.* 43, 22–28.
- Moiseev, I., 2023. Lorenz attractor plot. URL : [www.mathworks.com/matlabcentral/fileexchange/30066-lorenz-attractor-plot](http://www.mathworks.com/matlabcentral/fileexchange/30066-lorenz-attractor-plot).
- Prieur, M., 1976. Tribunal administratif de strasbourg - 6 juin 1975 : Ep. ott hubert et autres contre préfet du bas-rhin. avec note. *Revue juridique de l'Environnement* 1, 46–51. URL : [https://www.persee.fr/doc/rjenv\\_0397-0299\\_1976\\_num\\_1\\_1\\_1005](https://www.persee.fr/doc/rjenv_0397-0299_1976_num_1_1_1005), doi :10.3406/rjenv.1976.1005.
- Préfet coordonnateur de bassin Rhin-Meuse, 2012. Schéma directeur de prévision des crues du bassin Rhin-Meuse. URL : [https://www.vigicrues.gouv.fr/ftp/SDPC/SDPC\\_Rhin-Meuse.pdf](https://www.vigicrues.gouv.fr/ftp/SDPC/SDPC_Rhin-Meuse.pdf). (Accessed 2023-05-11).
- Préfet du Bas-Rhin, 2018. Dossier départemental des risques majeurs du Bas-Rhin. URL : <https://www.bas-rhin.gouv.fr/contenu/telechargement/29247/200793/>. (Accessed 2023-05-11).
- Schwabach, A., 1989. The Sandoz spill : The failure of international law to protect the Rhine from pollution. *Ecol. Law Quart.* 16, 443–480. doi :10.15779/Z38082W.
- Sendzimir, J., Magnuszewski, P., Gunderson, L., 2018. *Adaptive Management of Riverine Socio-ecological Systems*. Springer International Publishing, Cham. chapter 16. pp. 301–324. doi :10.1007/978-3-319-73250-3\_16.
- Sheps, A., 1999. Joseph priestley's time charts : The use and teaching of history by rational dissent in late eighteenth-century england. *Lumen : Selected Proceedings From the Canadian Society for Eighteenth-Century Studies* 18, 135. doi :10.7202/1012372ar.
- Shewhart, W.W.A., 1939. Statistical method from the viewpoint of quality control. The Graduate School, The Department of Agriculture. URL : <https://archive.org/details/CAT10502416>.
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the anthropocene : The great acceleration. *The Anthropocene Review* 2, 81–98. doi :10.1177/2053019614564785.
- Tansley, A.G., 1935. The use and abuse of vegetational concepts and terms. *Ecology* 16, 284–307. doi :10.2307/1930070.
- Tricart, J., Bravard, J.P., 1991. Le cours périalpin du Rhin, du Rhône et du Danube : aménagement fluvial et dérives de l'environnement. *Annales de géographie* 561-562, 668–713. URL : <https://www.jstor.org/stable/23452814>.
- Trieber, R., 2021. 420030003, Ile rhénane du Rohrschollen à Strasbourg. Technical Report. INPN, SPN-MNHN Paris. URL : <https://inpn.mnhn.fr/zone/znief/420030003.pdf>. (Accessed 2023-05-11).
- Uehlinger, U., Arndt, H., Wantzen, K.M., Leuven, R.S., 2009. Chapter 6 - the Rhine river basin, in : Tockner, K., Uehlinger, U., Robinson, C.T. (Eds.), *Rivers of Europe*. Academic Press, London, pp. 199–245. doi :<https://doi.org/10.1016/B978-0-12-369449-2.00006-0>.
- Unknown, 1931. La navigation fluviale entre strasbourg et bâle. *Géocarrefour* 7, 318–320. doi :10.3406/geoca.1931.3895.
- Westman, W., 1977. How much are nature's services worth ? *Science (New York, N.Y.)* 197, 960–964. doi :10.1126/science.197.4307.960.
- Wilkinson, M., Dumontier, M., Aalbersberg, I., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.W., da Silva Santos, L., Bourne, P., et al., 2016. The fair guiding principles for scientific data management and stewardship. *Scientific data* 3.

- doi:10.1038/sdata.2016.18.
- Williams, B.K., 2011. Adaptive management of natural resources—framework and issues. *J. Environ. Manage.* 92, 1346–1353. doi :10.1016/j.jenvman.2010.10.041. adaptive management for Natural Resources.
- World Resources Institute, 2005. Ecosystem and human well-being - synthesis. <https://wedocs.unep.org/20.500.11822/8701>. Accessed : 2023-05-11.
- Zimmermann, M., 1905. La régularisation du Rhin jusqu'à Strasbourg. *Annales de géographie* 14, 90–91. URL : [https://www.persee.fr/doc/geo\\_0003-4010\\_1905\\_num\\_14\\_73\\_6508](https://www.persee.fr/doc/geo_0003-4010_1905_num_14_73_6508).