Assessing land cover and climate change impacts on hydrological services provision using SWAT: insights from three watersheds in Portugal

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Outline

- Forests, hydrological services and management (PES schemes)
- Climate change and hydrological impacts in Portugal
- Case-studies in Portugal using SWAT
  - Hydrological impacts of scenarios of afforestation vs. agriculture
  - Hydrological impacts under climate change
  - Hydrological impacts of fire in scenarios of afforestation

Keywords: Forests, Hydrological services, SWAT, Environmental effectiveness, Climate change, Fire
Hydrological services

Water supply (quantity, quality and timing)

Flood protection

Hydropower generation

Erosion control

Irrigation
Hydrological cycle
Managed Ecosystems effects on water paths

Le Maître, et al. (2014)
Forest and hydrological services

**Properties**
- Biophysical structures
  - Vegetation density and structure
  - Rooting depth
  - Geological substrate
  - Soil properties (porosity, texture, hydraulic conductivity...)
  - Depth of unsaturated zone
  - Topography of the watershed
  - Precipitation pattern

- Processes
  - Evaporation
  - Transpiration
  - Throughfall
  - Surface runoff
  - Infiltration
  - Microbiota decomposition
  - Subsurface flow processes

**Functions**
- Forest capacity to store water (vegetation and soil)
- Forest shading effects to moderate stream temperature
- Capacity to trap sediments and break down pollutants
- Regulation of water flows (...)

**Services**
- Water supply
- Water damage mitigation

**Benefits**
- Water supply for household
- Hydropower generation
- Reduction in the number and severity of floods
- Less sediments in water bodies (...)

**Dimensions**
- Water:
  - Quantity
  - Timing
  - Quality

**Value**
Payments for Ecosystem Services (PES)

Carvalho-Santos et al., 2014
PES – Payments for Ecosystem Services

https://www.youtube.com/watch?v=gzNWnREZ2xl
Water PES types

Public subsidies for watershed protection reward land managers for enhancing or protecting ecosystem services. They are funded by governments (sometimes with multilateral or donor support), acting on behalf of the public good, and typically operate at a large scale.

User-driven watershed investments channel payments from water users, such as companies or water utilities acting on behalf of customers, to landholders or other parties (“sellers”) in exchange for conserving, restoring, or creating green infrastructure. Buyers may contract directly with sellers in a process known as bilateral agreements for watershed protection or pay into a collective action fund/water fund that pools contributions for greater impact. User-driven programmes can be voluntary or a mechanism to meet regulatory compliance.

Water quality trading and offsets allow water users to manage their impacts on watersheds by compensating others for offset activities that improve water quality or supply. Compensatory activities are packaged as a credit or some other unit traded in an established “market,” defined by watershed boundaries. Trading and offsets are often compliance-driven.

Governments through subsidies

Companies that pay representing their costumers

Compensations coming from users
Map 1: Public Subsidies for Watershed Protection in 2015: Countries by Value and Area under Management
Water PES through subsidies

4. MARKET OVERVIEW

Table 1: Mechanisms Tracked in This Report: Value, Area under Management, and Number of Operational Programmes in 2015

<table>
<thead>
<tr>
<th></th>
<th>Total Value, All Programmes</th>
<th>Total Area, All Programmes</th>
<th>Median Programme Value</th>
<th>Median Programme Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public subsidies for watershed protection</td>
<td>€5,668M</td>
<td>12.8M ha</td>
<td>€77.6M</td>
<td>417,020 ha</td>
</tr>
<tr>
<td>User-driven watershed investments</td>
<td>€38.4M</td>
<td>0.6M ha</td>
<td>€0.8M</td>
<td>3,500 ha</td>
</tr>
<tr>
<td>Water quality trading/offsets</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>TOTAL</td>
<td>€5,708M</td>
<td>13.4M ha</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: Data are not reported for water quality trading and offsets programmes in this table. Ecosystem Marketplace requires a minimum of three data points to report figures publicly in order to protect respondents’ confidentiality. Data was only collected for two programmes in the water quality trading and offsets mechanism category in 2015.

Figure 2: The Green-Grey Infrastructure Spectrum

<p>| Green | Green + Grey | Grey |</p>
<table>
<thead>
<tr>
<th>Focus Area</th>
<th>Associated Measures</th>
</tr>
</thead>
</table>
| Priority 4: Restoring, preserving, and enhancing ecosystems related to agriculture and forestry | Measure 8: Investments in forest areas  
Measure 10: Agri-environment-climate payments  
Measure 11: Organic farming  
Measure 12: Natura 2000 & WFD payments  
Measure 15: Forest-environmental and climate services and forest conservation practices |
| 4a: Restoring, preserving, and enhancing biodiversity, including in Natura 2000 areas, and in areas facing natural or other specific constraints, and High Nature Value farming, as well as the state of European landscapes | |
| 4b: Improving water management, including fertiliser and pesticide management | |
| 4c: Preventing soil erosion and improving soil management                  | |
| Priority 5: Promoting resource efficiency and supporting the shift towards a low-carbon and climate-resilient economy in agriculture, food, and forestry sectors | Measure 16: Cooperation [approaches among different actors in the Union agriculture sector, forestry sector, and food chain, and other actors that contribute to achieving the objectives and priorities of rural development policy] |
| 5a: Increasing efficiency in water use by agriculture                     | |


**Notes:** Focus Area 5a is also linked to Measure 4, “Investment in physical assets,” in EU rural development policy legislation. However, it is not tracked here as it is not possible to determine to what extent investment is in “green infrastructure” assets rather than built assets.
Water PES scheme in Portugal

The Green Heart of Cork project

The Coca-Cola Portugal – APFCertifica PES case

Type: Payment for bundle ecosystem services in voluntary market

- Partner providing the service: APFCertifica Group Scheme - Forests landowners formed an association and adopted sustainable forest management practices in order to receive Forest Stewardship Council (FSC) certification.
- Beneficiaries: Coca-Cola Portugal – Refins, beverage factory, located over the Tagus Aquifer (T3), consuming 500,000m³/year of groundwater.

Services: Forest landowners committed to maintain good forest management practices within the 16,000 ha FSC certified areas. FSC certification places a strong focus in criteria related to biodiversity conservation and watershed protection. Approximately 600 hectares (ha) were considered to be of critical importance for biodiversity and water recharge of the aquifer T3 and therefore were considered High Conservation Value Areas.

<table>
<thead>
<tr>
<th>HCV</th>
<th>High Conservation Value Areas (HCVAs) identified by APFC (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal Concentrations of Species</td>
<td>24.79</td>
</tr>
<tr>
<td>Watershed Protection</td>
<td>569.63</td>
</tr>
</tbody>
</table>

Location: Portugal, Alentejo and Ribatejo regions
Water PES scheme in Portugal

Coca-Cola paid 17€/ha to “montado” forest owners, high nature value areas above the biggest aquifer of the Iberian Peninsula

http://www.natureza-portugal.org/corporativo/green_heart_of_cork/
Motivation – water quality WFD targets

Map 2.1 Percentage of water bodies in Europe's RBDs that are not in good ecological status/potential second RBMPs

Map 4.1 River basin groundwater chemical status

Percentage of number water bodies not in good ecological status or potential per river basin district (RBD) in second RBMPs

Percentage of area of groundwater bodies not in good chemical status per river basin district (RBD) in second RBMPs

0% | 25% | 50% | 75% | 100%
---|---|---|---|---
RBD areas without data | No data | Outside coverage

Motivation – water quality WFD targets

Chemical state of water bodies in Portugal

Ecological status of surface waters
Would water supply service be affected by climate change, regarding the potential provision?

Would we have more drought problems?

Would we have more water quality problems?

Would we have more flood episodes?

Would soil erosion increase?

I was just kidding. I love rain! Come back!
Motivation – Climate change in Portugal

- Increase in temperature (2 to 4ºC until the end of century), specially in summer
- Decrease in precipitation with marked uneven annual distribution (more rain in winter and less rain during summer) – uncertain

Mediterranean type of climate with 2 to 4 dry months
Northern regions temperate and humid
Climate gradient wet to dry (north-south)

Climate Projections (RCP scenarios from 5 IPCC report)
Representative Concentration Pathways (RCP)

- RCP 4.5
- RCP 8.5

There are 34 General Circulation Models (GCMs).
Case studies using SWAT

Hydrological services provision under scenarios of land cover and climate change

Water supply by the reservoirs under future climate

Irrigation under future climate

Macieira (less than 1km²)
Methods

**SWAT**

- **DEM**
- **Land cover**
- **Soil**

**SWAT Input data**

- **HRU definition**
- **Forcing with climatic parameters**
  - **ET and Vegetation growth model**
    - **Curve number (CN)**
    - **MUSLE**

**SWAT Output data**

- **Streamflow**
- **Infiltration**
- **Evapotranspiration**
- **Sediments**
- **Surface runoff**
- **Nutrients** (…)

**Calibration** (manually changing sensitive parameters)

Source: ECAD/NCDC

Source: SNIRH

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Table 2. Potential hydrological services provision related to the SWAT outputs indicators presented in this study.

<table>
<thead>
<tr>
<th>Hydrological service</th>
<th>SWAT outputs/indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water supply</strong></td>
<td></td>
</tr>
<tr>
<td>Quantity</td>
<td>Total annual water yield (mm) and monthly discharge (m³/s)</td>
</tr>
<tr>
<td>Timing</td>
<td>Flow duration curves (Q95 - m³/s); soil water content (mm)</td>
</tr>
<tr>
<td>Quality</td>
<td>Nitrate concentration (mgN/l); nitrogen export (kg/ha.yr )</td>
</tr>
<tr>
<td>Water damage mitigation</td>
<td></td>
</tr>
<tr>
<td>Erosion control</td>
<td>Soil erosion (t ha.yr); % of the basin under soil erosion risk</td>
</tr>
<tr>
<td>Flood regulation</td>
<td>Flow duration curve (Q5 - m³/s); soil water content (mm)</td>
</tr>
</tbody>
</table>
Vez watershed
### Scenarios

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Current</th>
<th>Oak Conservation</th>
<th>Eucalyptus/pine Intensification</th>
<th>Agri/vine Corn/vineyard</th>
<th>Low vegetation Degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORN</td>
<td>18.7</td>
<td>18.7</td>
<td>18.7</td>
<td>18.7</td>
<td>18.7</td>
</tr>
<tr>
<td>EUCL/PINE</td>
<td>8</td>
<td>-</td>
<td>63.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OAK</td>
<td>8.7</td>
<td>63.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BSVG</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>60.6</td>
</tr>
<tr>
<td>MIGS</td>
<td>47.2</td>
<td>-</td>
<td>-</td>
<td>16.7</td>
<td>16.7</td>
</tr>
<tr>
<td>VINE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>46.8</td>
<td>-</td>
</tr>
</tbody>
</table>

**RCP 4.5 scenario (ensemble of 4 GCMs)**

<table>
<thead>
<tr>
<th>Season</th>
<th>2021-40</th>
<th>2041-60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ΔPrec (%)</td>
<td>ΔTMAX (°C)</td>
</tr>
<tr>
<td>Winter (Jan – Mar)</td>
<td>7.88</td>
<td>0.83</td>
</tr>
<tr>
<td>Spring (Apr – Jun)</td>
<td>-4.85</td>
<td>1.13</td>
</tr>
<tr>
<td>Summer (Jul – Sep)</td>
<td>-9.73</td>
<td>1.25</td>
</tr>
<tr>
<td>Autumn (Oct – Dez)</td>
<td>2.63</td>
<td>0.93</td>
</tr>
<tr>
<td>Annual</td>
<td>1.20</td>
<td>1.03</td>
</tr>
</tbody>
</table>
SWAT calibration and validation

Vez watershed

Calibration

NSE: 0.73
PBIAS: -15%

Validation

NSE: 0.38
PBIAS: 6%

Sediment comparison (Outlet 10)

NSE: 0.13
PBIAS: 65%

Nitrate comparison (Outlet 10)

NSE: 0.38
PBIAS: 30%

NSE: -1.9
PBIAS: 102%

Nitrate comparison (Outlet 10)

NSE: 0.38
PBIAS: -13%
Results – Vez watershed

Land-cover scenarios

Reduction in the water quantity with an attenuation in the peak flows (winter months) are expected with the eucalyptus/pine scenario.
Results – Vez watershed

Land-cover scenarios

<table>
<thead>
<tr>
<th>Land-cover scenario</th>
<th>Water quality</th>
<th>Soil erosion control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO$_3$-N (mg/l)</td>
<td>Nº days with NO$_3$-N exceeding 5.6 mg/l</td>
</tr>
<tr>
<td>Current cover</td>
<td>1.9</td>
<td>74</td>
</tr>
<tr>
<td>Eucalyptus/pine</td>
<td>2.1</td>
<td>104</td>
</tr>
<tr>
<td>Oak</td>
<td>1.9</td>
<td>64</td>
</tr>
<tr>
<td>Agri/vine</td>
<td>2.2</td>
<td>68</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>1.7</td>
<td>52</td>
</tr>
</tbody>
</table>

Soil erosion will slightly increase, mainly due to winter precipitation

Nitrate concentration in the river will increase
Results – Vez watershed

Climate change scenarios

Small **decrease of annual water quantity** (-2 to -7%)

**Aggravation of the low flows** during summer and **increase peak flows** during winter
Results – Vez watershed

Future climate will reduce the low flows, aggravated with forestation scenario.

Future climate will increase soil erosion and nitrate concentration, aggravated with agriculture scenario.

Promoting forests can attenuate peak flows (flood mitigation) during winter.

Results emphasize the importance of building adaptation strategies that consider both climate and land cover changes.
Sabor watershed
Scenarios

SWAT applied to Alto Sabor watershed

Climate change impacts on water supply
scenarios:
• 1 and/or 2 reservoirs
• 4 climatic models
• RCP 4.5 e 8.5 scenarios

Land cover change effects on hydrological services
scenarios:
• Native Forest
• Land Abandonment
• Semi-natural
Calibration – Sabor watershed

Calibração (1997-2007)

NSE: 0.66
PBIAS: -21%

GIMONDE

NSE: 0.62
PBIAS: -19%

Simulado
Observado
Precipitação

Validação (1986-1996)

NSE: 0.83
PBIAS: 8%

NSE: 0.59
PBIAS: 9%

RABAL

Simulado
Observado
## Results – Sabor watershed

### Land-cover scenarios

<table>
<thead>
<tr>
<th>Ecosystem Services</th>
<th>Indicator (Unit)</th>
<th>Baseline (agriculture)</th>
<th>Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Native Forest</td>
</tr>
<tr>
<td><strong>Water supply</strong></td>
<td>Water quantity (hm³ yr.)</td>
<td>170.96</td>
<td>183.50</td>
</tr>
<tr>
<td><strong>Water quality</strong></td>
<td>NO₃ in the river (mg/l)</td>
<td>1.09</td>
<td>1.10</td>
</tr>
<tr>
<td><strong>Soil erosion control</strong></td>
<td>Sediment retention (t/h yr.)</td>
<td>2.05</td>
<td><strong>2.67</strong></td>
</tr>
</tbody>
</table>

Native forest scenario is the best for hydrological services provision, in particular for water quantity and soil erosion control.
Results – Sabor watershed

Climate change scenarios

General reduction of reservoir volume during spring and summer for the period 2041-2060
More water during winter under RCP 8.5
The existence of two reservoirs will solve the water supply problems in current climate conditions, but in the future the reliability of this solution will decrease (reliability of water supply below 90%).

Here, the variability given by the different climate models brings some uncertainty (grey dots).
Reservoirs Monte Novo and Vigia

Climate change impacts on water in the reservoirs

- 2 climatic models
- RCP 4.5 and 8.5 scenarios
Reservoirs Monte Novo and Vigia

More water available in RCP 4.5 (winter)
Less water available in RCP 8.5

Water Exploitation Index (WEI) (water use/water availability)
Irrigated crops will use more water in the future, mainly during summer when precipitation will decrease:

- anticipate their cultivation in 1/2 months to take advantage of the increasing precipitation and temperature during winter
- water transfers from a major reservoir (Alqueva), but costs must be considered
- the increase of irrigated area should not be more than 3% of the area (WEI – 50%)
- Farmer’s plans - increase of permanent irrigated crops (olive, hazelnut), but water use all over the year
Hydrological impacts of fire in scenarios of afforestation and management

Macieira watershed

Nunes et al., 2018
Calibration and validation

Rainfall (mm) vs. Streamflow ($m^3/s$)

Rainfall (mm) vs. Sediment yield (ton $d^{-1}$)

Calibration and Validation

No data
Hydrological impacts of fire in scenarios of afforestation and management

Macieira watershed

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Erosion (ton ha(^{-1}) yr(^{-1}))</th>
<th>Average 2004/2014</th>
<th>Before fire</th>
<th>1(^{st}) year after fire(^a)</th>
<th>2(^{nd}) and 3(^{rd}) years after fire(^b)</th>
<th>Early pasture</th>
<th>Late pasture</th>
<th>Corn plantation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt</td>
<td>Unburnt</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Burnt, plowed</td>
<td>14.0</td>
<td>0.1</td>
<td>22.9</td>
<td>76.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Burnt, unmanaged</td>
<td>8.2</td>
<td>0.1</td>
<td>18.2</td>
<td>41.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pine</td>
<td>Unburnt</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Burnt, plowed</td>
<td>5.9</td>
<td>0.1</td>
<td>0.1</td>
<td>39.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Burnt, unmanaged</td>
<td>3.8</td>
<td>0.1</td>
<td>0.1</td>
<td>24.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pasture</td>
<td>Normal</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Terraced</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corn rotation</td>
<td>Normal</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Terraced</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fire led to erosion rates in forests **higher** than those in agricultural fields

Nunes *et al.*, 2018
Portuguese Government will directly compensate owners to create/maintain resilient forest against fire, indirectly promoting water ecosystem services.

Forests with native species more resilient to fire
Take home messages

Hydrological models, when properly calibrated to the local conditions, can be used to **assess environmental effectiveness of woodland measures and climate change impacts**.

Modelled scenarios of **afforestation show less sediment and nitrogen loads**, when compared to agriculture.

**Fires may negatively affect the provision of hydrological services** provided by forests, in particular soil erosion and the quality of water, for levels worst than agriculture (different contaminants).

**PES schemes** should incorporate **fire risk** in their elaboration for the Mediterranean regions.
Acknowledgments

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Project Ind_Change (2013-2015)

Project Gestqua.AdaPT (2015-2016)

Project ECOPOTENTIAL (2016 ...)