Quantifying the effects of land-use change and climate variability on water resources in the Pyrenees

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1. INTRODUCTION

- Mountains provide half of the world’s population with water resources

- Major changes have been observed in the variables and processes that shape the hydrological cycle

- In the Pyrenees there is a general decline in water resources which cannot be explained alone by climatic causes

- This study quantifies independently the contribution of both of these factors

2. STUDY AREA: Anduña River basin

- Located in the western Pyrenees, Spain (4,728.61 ha).
- Orographically complex
- Atlantic Climate
- Land-Use Evolution: Shift from agrarian to forest since 1956
- Giving rise to a land primarily occupied by forests (conifers and hardwoods)
3. DATA AND METHODS

Figure 2. Flowchart of the methodology

**DATA AND MODEL PREPARATION**

**STEP 1:** Trend analysis
- Climate trend analysis
- Climate data
- Land Use data
- Soil data
- DEM

**STEP 2:** SWAT model

**SCENARIOS**

**STEP 3:**
- Climate data: 1951-1985
  - Land use data: 1956
- Climate data: 1986-2021
  - Land use data: 1956
- Climate data: 1986-2021
  - Land use data: 2000

**Scenario A**
- CC

**Scenario B**
- LULC

**Scenario C**
- All factors

**IMPACTS**

Aplication of IAHRS for IHA calculation
3. DATA AND METHODS

QUANTIFYING THE EFFECTS OF LAND-USE CHANGE AND CLIMATE VARIABILITY ON WATER RESOURCES IN THE PYRENEES

Figure 2. Flowchart of the methodology
3. DATA AND METHODS

3.1. Trend analysis of climate variables

- Climate variables: Maximum temperature, minimum temperature and precipitation
- Mann-Kendall trend test
- Significance assessed using the Z-test
- Sens' slope employed to estimate the magnitude of linear trends, providing a robust measure less sensitive to outliers.
3. DATA AND METHODS

3.2. SWAT model

- Input Data for SWAT Model:
  - **DEM** data obtained from the Spanish Geographical Institute with a spatial resolution of 25 m x 25 m.
  - Harmonized World **Soil Map** used with a spatial resolution of 1 km x 1 km.
  - **Climate data**: Maximum temperature, minimum temperature, and precipitation data for 1951-1985 and 1986-2020 obtained from AEMET with a spatial resolution of 5 km x 5 km and daily temporal frequency.
  - **Land-use data**: Reference land-use maps from 1956 and 2000 obtained from the Government of Navarre regional sources.
  - **Discharge observations** of Izalzu outlet (CEDEX)

![Flowchart of the methodology](image)
3. DATA AND METHODS

3.2. SWAT model

- Calibration and validation
  - SWAT-CUP → SUFI-2 algorithm
  - Sensitivity analysis (500 iterations)
  - Objective function: KGE
  - 1,000 iterations: 500 + 500

\[
\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}
\]

\[
\text{PBIAS} = \frac{\sum_{i=1}^{n}(O_i - S_i)}{\sum_{i=1}^{n}(O_i)} \times 100
\]

\[
R^2 = \left( \frac{\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2}} \right)^2
\]

\[
\text{KGE} = 1 - \sqrt{(r - 1)^2 + \left( \frac{\bar{O}}{\bar{S}} - 1 \right)^2 + \left( \frac{\bar{S}}{\bar{O}} - 1 \right)^2}
\]

Figure 2. Flowchart of the methodology

3. DATA AND METHODS

3.4. Indicators of hydrological alteration: IAHRIS

- Provides information on the degree of alteration between a simulated and baseline scenario (Scenario A, B and C)
- Was developed in Spain to address the requirements of the European Water Framework Directive
- IAHRIS establishes the IHA related to the maximum extreme (floods), minimum extreme (droughts), and usual values

IGA: Index on Global Alteration

0 → Maximum disturbance
1 → No disturbance

4. RESULTS

4.1. Trend analysis

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Test Z</th>
<th>Sig.</th>
<th>$Q_i$</th>
<th>Maximum Temperature</th>
<th>Test Z</th>
<th>Sig.</th>
<th>$Q_i$</th>
<th>Minimum Temperature</th>
<th>Test Z</th>
<th>Sig.</th>
<th>$Q_i$</th>
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<tr>
<td>jan</td>
<td>1.350</td>
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<td>2.134</td>
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<td>0.019</td>
<td></td>
<td>2.809</td>
<td>**</td>
<td>0.028</td>
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<tr>
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<td>0.012</td>
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<td>0.018</td>
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<tr>
<td>apr</td>
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<td>4.070</td>
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<td>0.041</td>
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<td>3.946</td>
<td>***</td>
<td>0.025</td>
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<td>0.000</td>
<td></td>
<td></td>
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<td></td>
<td>0.655</td>
<td>0.006</td>
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<tr>
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<td></td>
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<td>0.026</td>
<td></td>
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<td>3.018</td>
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<td>0.025</td>
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<td>0.000</td>
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<td></td>
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<td>0.012</td>
<td></td>
<td></td>
<td>1.648</td>
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<tr>
<td>annual</td>
<td>1.896</td>
<td>**</td>
<td>0.009</td>
<td></td>
<td>4.735</td>
<td>***</td>
<td>0.028</td>
<td></td>
<td>5.490</td>
<td>***</td>
<td>0.021</td>
</tr>
</tbody>
</table>

Table 3: Trend analysis results.

[6] Lemus-Canovas et al., 2019
4. RESULTS

4.2. Land-use change

Table 2. Land-use type data

<table>
<thead>
<tr>
<th>Land Cover Type</th>
<th>Area Coverage km² (%)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Soil</td>
<td>15 (0.3%)</td>
<td>23 (0.5%)</td>
</tr>
<tr>
<td>Broad-leaved Forest</td>
<td>1604 (33.2%)</td>
<td>1872 (38.8%)</td>
</tr>
<tr>
<td>Coniferous Forest Evergreen</td>
<td>334 (6.9%)</td>
<td>1331 (27.5%)</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>171 (3.5%)</td>
<td>347 (7.2%)</td>
</tr>
<tr>
<td>Pasture</td>
<td>2101 (43.5%)</td>
<td>1075 (22.3%)</td>
</tr>
<tr>
<td>Shrub</td>
<td>607 (12.6%)</td>
<td>183 (3.8%)</td>
</tr>
</tbody>
</table>

Figure 3. : Land-use change tranformation.
4. RESULTS

4.3. Calibration and validation

Table 3. Calibration parameters code, description, initial calibration range and final optimal value

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Calibration Range</th>
<th>Adjusted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esco</td>
<td>Soil evaporation compensation factor</td>
<td>0 – 1</td>
<td>0.7543</td>
</tr>
<tr>
<td>Epeo</td>
<td>Plant uptake compensation factor</td>
<td>0 – 1</td>
<td>0.7325</td>
</tr>
<tr>
<td>Cn2</td>
<td>Initial SCS runoff curve number condition II</td>
<td>±20 %</td>
<td>19.88</td>
</tr>
<tr>
<td>Awc</td>
<td>Available water capacity</td>
<td>±20 %</td>
<td>12.04</td>
</tr>
<tr>
<td>Snofallmp</td>
<td>Snowfall temperature (°C)</td>
<td>-5 – 5</td>
<td>0.491</td>
</tr>
<tr>
<td>Snomeltmp</td>
<td>Snowmelt base temperature (°C)</td>
<td>-5 – 5</td>
<td>2.465</td>
</tr>
<tr>
<td>Snomelmax</td>
<td>Maximum melt rate of snow during a year (mm °C-1 day -1)</td>
<td>0 – 10</td>
<td>5.206</td>
</tr>
<tr>
<td>Snomelmin</td>
<td>Minimum melt rate of snow during a year (mm °C-1 day -1)</td>
<td>0 – 10</td>
<td>1.276</td>
</tr>
<tr>
<td>Snomeltlag</td>
<td>Snow pack temperature lag factor</td>
<td>0 – 1</td>
<td>0.973</td>
</tr>
</tbody>
</table>

Table 4. Calibration and validation statistical values on a daily basis

<table>
<thead>
<tr>
<th>Period</th>
<th>R²</th>
<th>NSE</th>
<th>PBIAS</th>
<th>KGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration (1992-2004)</td>
<td>0.72</td>
<td>0.51</td>
<td>-12.67</td>
<td>0.55</td>
</tr>
<tr>
<td>Validation (2005-2018)</td>
<td>0.75</td>
<td>0.55</td>
<td>-16.49</td>
<td>0.62</td>
</tr>
</tbody>
</table>

[7] Kallin et al., 2010

Parameters derived from the Sensitive analysis
Parameters selected from literature

Simulation of Scenarios A, B and C

Very good
Satisfactory
4. RESULTS

4.4. Impacts of land-use change and climate variability on hydrological regime

**Annual Balance of the Scenarios**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>P</th>
<th>ET</th>
<th>Runoff</th>
<th>Change ET</th>
<th>Change Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1718.3</td>
<td>576.6</td>
<td>1100.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1722.2</td>
<td>592.1</td>
<td>1079.1</td>
<td>15.5</td>
<td>-21.2</td>
</tr>
<tr>
<td>C</td>
<td>1722.2</td>
<td>607.6</td>
<td>1064.1</td>
<td>31.0</td>
<td>-36.1</td>
</tr>
</tbody>
</table>

Table 5. Simulated average annual runoff and ET under Scenarios A, B and C (mm)

**Flood alteration**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>$Q_c$</th>
<th>ED</th>
<th>CD</th>
<th>FF</th>
<th>CV($Q_c$)</th>
<th>CV(FF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.21</td>
<td>10.05</td>
<td>13.50</td>
<td>4.31</td>
<td>0.40</td>
<td>0.24</td>
</tr>
<tr>
<td>B</td>
<td>15.90</td>
<td>15.30</td>
<td>20.00</td>
<td>4.25</td>
<td>0.44</td>
<td>0.23</td>
</tr>
<tr>
<td>C</td>
<td>15.06</td>
<td>14.40</td>
<td>18.80</td>
<td>4.22</td>
<td>0.43</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 6. Flood parameters of over A, B and C scenarios (mm)

- Precipitation increases minimally
- Rise of temperatures lead to an increase in ET
- The contribution of each of the factors in the increase of ET was 50%
- In the runoff decrease, land-use impact (41.36%) was almost as important as climate variability (58.64%)
- Climate variability generated increases of more than 40% in the variables $Q_c$ (Average of the max. daily flow), ED and CD
- The alteration of these variables is slightly mitigated, with decrease values around 5% by reforestation
4. RESULTS

4.5. Indicators of hydrological alteration

Figure 4. Spider charts of IHAs and IGA values for habitual values, floods and droughts for Impact A-B and Impact A-C.
4. RESULTS

4.5. Indicators of hydrological alteration

- V1 (variability of annual volume) is driven by climatic causes.
- V2 (monthly volume variability) is determined by land-use change.

Figure 4: Spider charts of IHAs and IGA values for habitual values, floods and droughts for Impact A-B and Impact A-C.
4. RESULTS

4.5. Indicators of hydrological alteration

- The most altered regime
- Alteration entirely due to climatic causes
- Slightly alleviated by reforestation process
- IHA9 (Magnitude of Connectivity Flow) is the most affected
- IHA7 (Magnitude of maximum floods) and IHA8 (Magnitude of effective discharge)

CONSEQUENCES:
- Deficiencies on the transport to the floodplain and riparian river system
- Successional dynamics and aging of riparian habitat

[8] Larsen et al., 2019
4. RESULTS

4.5. Indicators of hydrological alteration

- The major alterations occurred in magnitude and frequency
- The combined effect of both factors exacerbate the alterations on the hydrological regime

Figure 4: Spider charts of IHAs and IGA values for habitual values, floods and droughts for Impact A-B and Impact A-C.
4. RESULTS

4.5. Indicators of hydrological alteration

- **H6 (variability of streamflow for each month):**
  - Increases were observed during March, June and October while decreases in variability were detected for winter months

- **H8 / H9 (Maximum/ Minimum relative frequency of the month):**
  - As a consequence of climate variability the probability of the annual maximum occurring in April increases
  - The probability of the minimum in September increases

**CONSEQUENCES:**
- These alterations in the natural seasonal patterns could produce distortions on the synchrony with the life cycle of the species

![Figure 5. Monthly values for IAHRIS parameters under A, B and C scenario](image)
5. Conclusions

- The favorable results of the model of the Anduña River Basin validate it for the daily simulation of the Scenarios.
- The climate trend analysis revealed a significant positive trend for maximum and minimum temperatures and a slight positive trend in precipitation (Lemus-Canovas et al., 2018).
- A radical transformation of the distribution of land-use in the basin was observed, from a land dominated by pastures and shrubs to a basin where forests are predominant.
- Climate change and the greenness process have decreased the mean annual streamflow in the Anduña River basin.
- The contribution of climate change is of 58.6%, while the contribution attributed to the greenness process is of 41.1% (Juez et al., 2022; Vicente-Serrano et al., 2021; López-Moreno et al., 2008).
- Increase of floods caused by climatic causes (Roy et al., 2001; Stoffel et al., 2016). This increase is attenuated by the reforestation process.
- In the cases of the usual values and extreme minimums (droughts), the reforestation process acted as an aggravating factor in altering the water regime, together with climatic causes.
5. References


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