Impact of forest management practices on stream water quality:

First results of generalized additive mixed models (GAMMs)

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Problem and research focus

- Forested catchments are considered to guarantee the high quality of surface and drinking water.
- Atmospheric input of acid deposition: long-term risk for stream acidification!
- Forest management practices improve water quality

We aim to
determine trends of stream acidification depending on

- management practices
- site conditions

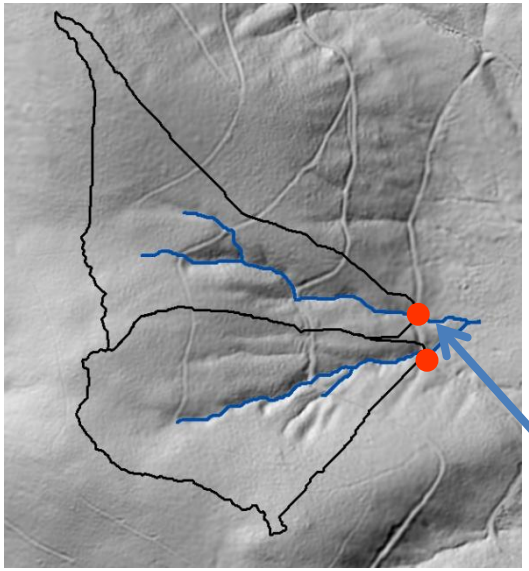
on the basis of statistical analyses.

Research questions

- Can we observe a significant impact of liming, storms and bark beetle infestation on water quality?
- What are the main influencing variables (e.g. deposition, geology,…) for water quality?

Investigation sites

- Water quality data of 86 streams (●)
- forested mountain ranges



Germany

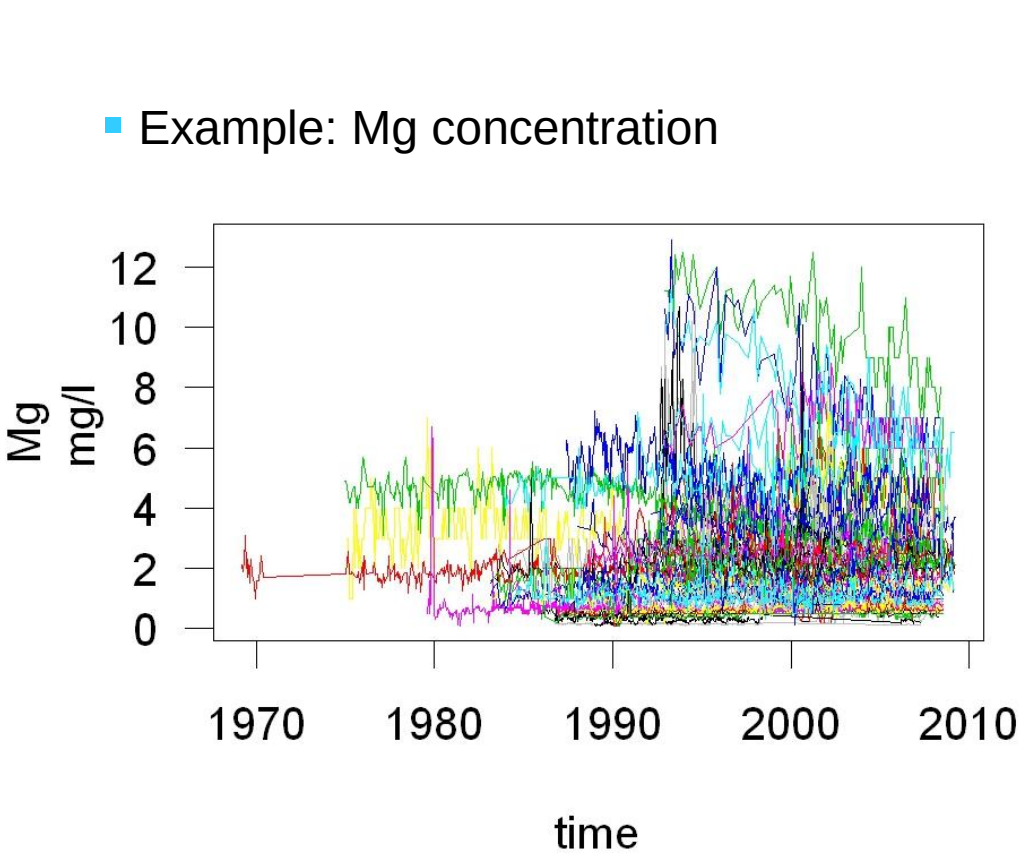
- Indicators of stream water quality

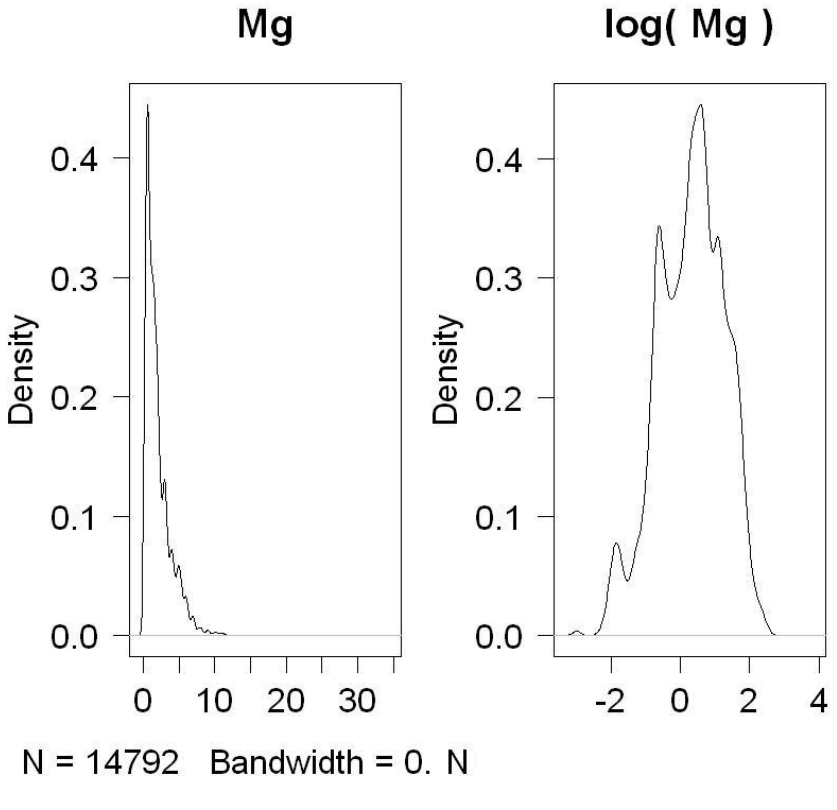
- Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, Cl^-
- Quotient of acidification:

  $QA = (Ca^{2+} + Mg^{2+}) / (SO_4^{2-} + NO_3^- + Cl^-)$
- pH value
- Acidification products (Al^{3+}, Mn^{2+})
- Conc. of humic substances (DOC)

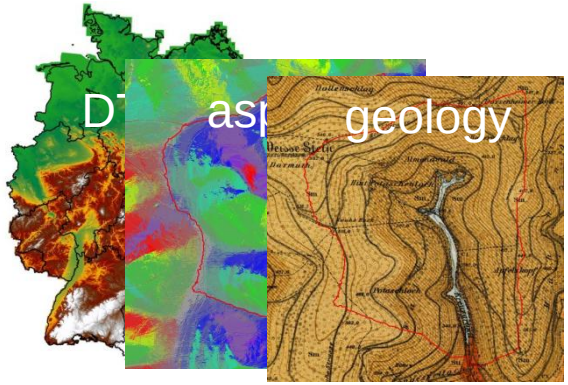
Observed concentrations

- varying reporting levels
- sampling frequencies from weekly to monthly
- individual observation period started between 1969 and 2001 and ended 1990 and 2009
- Example: Mg concentration

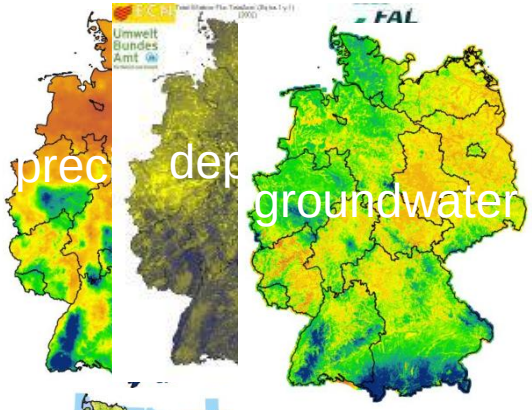




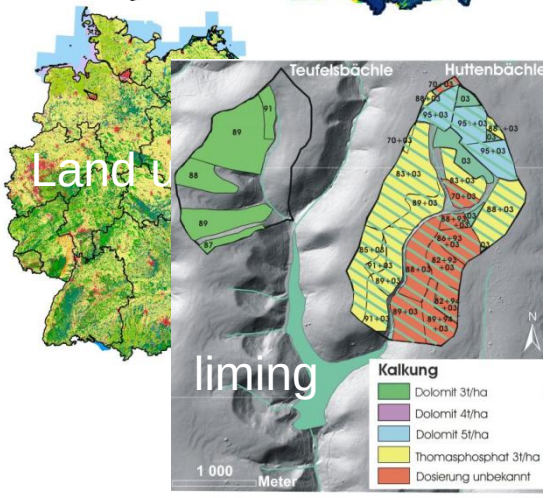
Explanatory variables



- Descriptive factors of catchment (area, height, location, perimeter, shape, slope, aspect)
- Soil types, soil water (field capacity, available field capacity, air capacity, rate of percolation, depth of the effective root zone) and base saturation (BZE I sites)
- Geology, drainage density and silicate weathering rates



- Meteorology (precipitation, temperature, sunshine duration, pot. and act. evaporation, climatic water balance)
- Deposition and critical loads of pot. acidity
- Runoff depth, low-flow MN10q, BaseFlowIndex and groundwater recharge



Potential forest management drivers for stream water quality

Controllable drivers

- Land use (CORINE 1990, 2000 and site description from publications)
- Liming for soil protection purposes

Uncontrollable drivers

- Natural disturbance of stand structure (Storm and bark beetle infestation)

BZE = first national soil inventory (1989-1992)

Correlation

Diluting effect:

Acidification effect:

log(Mg-concentration)

precipitation

total deposition

Method: GAMMs

$y \sim \gamma(\mu)$

$log(y) = g(y) = \eta,\ y = g^{-1}(\eta) = exp(\eta)$

Linear predictor for location *i* and time *t:*

$\eta_{it} = \beta_0 + \beta_1 \times I(precipitation) + \beta_2 \times I(total\ deposition) + \ldots \beta_{p-1} x_{it}^{(p-1)} + b_{it}$

random effect on location *i:* $b_{i\,t} \sim N(0, \tau^2)$

First Models

```
Fit.GAMM.1 <-gamm(Mg~s(precipitation),
        family = Gamma(link = "log"),
        data=Daten)
```

```
Fit.GAMM.2 <- gamm(Mg~s(precipitation),
        family = Gamma(link = "log"),
        random=list(stream number=~1),
        data=Daten)
```

R-sq.(adj) = 0.0416

s(precipitation, 7.12)

AIC	BIC	logLik
51296.65	51328.24	-25644.33

precipitation

R-sq.(adj) = 0.00432

s(precipitation, 1)

AIC	BIC	logLik
32258.04	32297.53	-16124.02

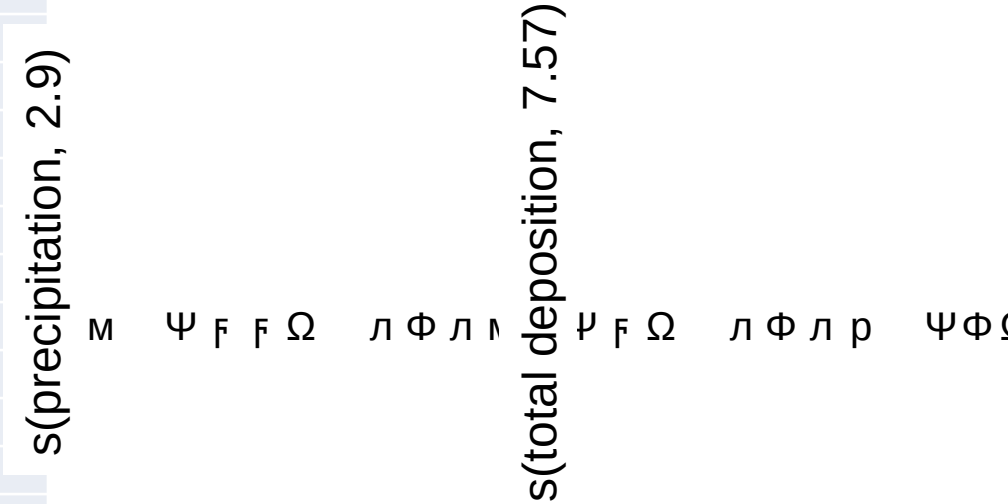
precipitation

Fit.GAMM.3 <--gamm(Mg~s(precipitation)+s(total deposition), family = Gamma(link = “log“), random=list(stream number=~1), data=Daten)

```
Family: Gamma
Link function: log

Formula:
Mg ~ s(P) + s(acid)

Parametric coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.5866     0.0911   6.439 1.28e-10 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                    edf Ref.df     F  p-value
s(precipitation)  2.904  2.904 13.43 2.16e-08 ***
s(total deposition) 7.571  7.571 12.22 < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.00508   Scale est. = 0.04152   n = 631
```

n = 19872

Data available for 1995, 1997, 1999 - 2004



precipitation total deposition

```
Linear mixed-effects model fit by maximum likelihood
 Data: data
      AIC       BIC   logLik
 -2010.046 -1961.466 1012.023

 Formula: ~1 | V %in% g.0 %in% g
        (Intercept)  Residual
StdDev   0.8143698 0.2037639
```

```
Fit.GAMM.4 <- gamm(Mg~s(precipitation)+s(total deposition),family = Gamma(link = "log"),
random=list(stream number=~1), correlation=corCAR1(form=~Date|stream number),data=Daten)
```

```
Family: Gamma
Link function: log

Formula:
Mg ~ s(precipitation) + s(total deposition)

Parametric coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.59358    0.08977   6.612 4.14e-11 ***
---
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Approximate significance of smooth terms:
           edf Ref.df     F p-value
s(P)     1.000  1.000 3.788  0.0517 .
s(acid) 3.858  3.858 10.180 7.1e-08 ***
---
{ ǻ ∃ y′ ǻ ∓ Φ  Ŏ ⁄ Ř Ŝ ă Y  л  Ψ ┣ ┣ ┣ Ω  л

R-sq.(adj) =  0.0185   Scale est. = 0.049065  n = 7631
```

precipitation total deposition

```
Linear mixed-effects model fit by maximum likelihood
 Data: data
       AIC       BIC   logLik
 -5046.388 -4990.868 2531.194

 Formula: ~1 | V %in% g.0 %in% g
        (Intercept)  Residual
StdDev   0.8016922 0.2215068
```

Questions

- How can I include the aspect variable?
  - → sinus transformation of aspect =0.5(1+sin(aspect)-90°C))
  - → 0 = south, 1 = north

    “Fehler in smooth.construct.tp.smooth.spec(object, dk$data, dk$knots) : A term has fewer unique covariate combinations than specified maximum degrees of freedom”

- How to handle with percentage values (0%, …, 100%)?
  - → Used it for mapped information (geology, soil type, land use, liming, storm area, bark beetle infestation)
  - → as factor()?

- How to deal with error messages when including the correlation term?

  “Fehler in Initialize.corCAR1(X[[2L]], ...) : covariate must have unique values within groups for "corCAR1" objects”

- How to get good model?

Thanks for provision of data !

Bavaria:

- Büro für Angewandte Hydrologie München
- Nationalparkverwaltung Bayerischer Wald
- Landesamt für Umwelt
- Bayerische Landesanstalt für Wald und Forstwirtschaft

Saxony:

- Landestalsperrenverwaltung des Freistaates Sachsen
- Staatsbetrieb Sachsenforst
- Dresden University of Technology

Saxony-Anhalt:

- Talsperrenbetrieb Sachsen-Anhalt (AöR)

Thuringia:

- Thüringer Fernwasserversorgung

Rhineland-Palatinate:

- Stadtwerke Idar-Oberstein
- SWT Stadtwerke Trier Versorgungs-GmbH LUWG
- Landesamt für Umwelt, Wasserwirtschaft und Gewerbeaufsicht Rheinland-Pfalz

North-Rhine-Westfalen:

- WSW Energie & Wasser AG
- WAG Nordeifel mbH
- Wasserverband Aabachtalsperre

Baden-Württemberg:

- Zweckverband Wasserversorgung Kleine Kinzig
- Limnologie-Büro Hoehn
- Forstliche Versuchs- und Forschungsanstalt BW
- LfU (Landesanstalt f. Umweltschutz Baden-Württemberg, Karlsruhe Abt 4 Wasser)
- LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg

Lower Saxony:

- Forest Research Institute of Lower Saxony

Other data sources:
DWD: German Weather Service
HAD: Hydrological Atlas of Germany
UBA: Umweltbundesamt
vTI: Johann Heinrich von Thünen-Institut, Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei