Uncertainty in global irrigation withdrawals persists after 50 years of research

R code

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Contents

1 Preliminary functions

```
#   PRELIMINARY FUNCTIONS ##########################################################

sensobol::load_packages(c("openxlsx", "data.table", "tidyverse","cowplot",
                          "benchmarkme", "parallel", "wesanderson", "scales", "ncdf4",
                          "countrycode", "rworldmap", "sp", "doParallel", "here", "lme4",
                          "microbenchmark", "mgcv", "brms", "randomForest"))

# Create custom theme ----------------------------------------------------------

theme_AP <- function() {
  theme_bw() +
    theme(panel.grid.major = element_blank(),
          panel.grid.minor = element_blank(),
          legend.background = element_rect(fill = "transparent",
                                           color = NA),
          legend.key = element_rect(fill = "transparent",
                                    color = NA),
          strip.background = element_rect(fill = "white"),
          legend.text = element_text(size = 7.3),
          axis.title = element_text(size = 10),
          legend.key.width = unit(0.4, "cm"),
          legend.key.height = unit(0.4, "cm"),
          legend.key.spacing.y = unit(0, "lines"),
          legend.box.spacing = unit(0, "pt"),
          legend.title = element_text(size = 7.8),
          axis.text.x = element_text(size = 7),
          axis.text.y = element_text(size = 7),
          axis.title.x = element_text(size = 7.3),
          axis.title.y = element_text(size = 7.3),
          plot.title = element_text(size = 8),
          strip.text.x = element_text(size = 7.4))
}

# Select color palette ---------------------------------------------------------

selected.palette <- "Darjeeling1"
```

```
# SOURCE ALL R FUNCTIONS NEEDED FOR THE STUDY ###################################

# Source all .R files in the "functions" folder --------------------------------

r_functions <- list.files(path = here("functions"), pattern = "\\.R$", full.names = TRUE)
lapply(r_functions, source)
```

2 ISIMIP Data

2.1 Historical data

```
# RETRIEVE DATA FROM ISIMIP ############################################################

# Create vector with list of files -------------------------------------------

list.of.files <- list.files("./files/isimip")
model.names <- sub("^(.*?)_.*", "\\1", list.of.files)
climate.scenarios <- sapply(strsplit(list.of.files, "_"), function(x) x[2])
social.scenarios <- sapply(strsplit(list.of.files, "_"), function(x) x[which(x == "co2") - 1])
files.directory <- paste("./files/isimip", list.of.files, sep = "/")
start_year <- 1971

# Create parallel cluster ----------------------------------------------------

numCores <- detectCores() * 0.75
cl <- makeCluster(numCores)
registerDoParallel(cl)

# Run for loop ---------------------------------------------------------------

isimip.hist <- foreach(i = 1:length(files.directory),
                       .packages = c("data.table", "countrycode", "tidyverse",
                                     "sp", "rworldmap", "ncdf4")) %dopar% {

                                       get_isimip_fun(nc_file = files.directory[i],
                                                      variable = "airrww",
                                                      start_year = start_year)
                                     }

# Stop the cluster after the computation -------------------------------------

stopCluster(cl)
```

```
# ARRANGE DATA #########################################################################

# Number of files ------------------------------------------------------------

list.of.files
```

```
##  [1] "dbh_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [2] "dbh_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [3] "dbh_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
##  [4] "dbh_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [5] "dbh_wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc"
##  [6] "h08_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [7] "h08_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [8] "h08_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
```

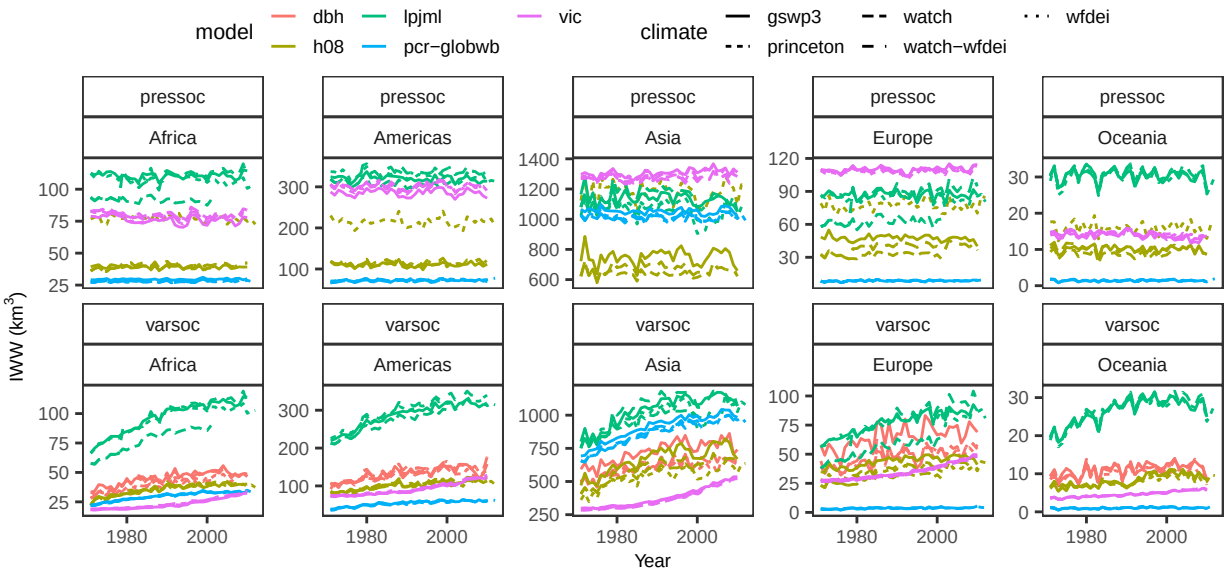
```
##  [9] "h08_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012(1).nc4"
## [10] "h08_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [11] "h08_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [12] "h08_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [13] "h08_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [14] "h08_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [15] "h08_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
## [16] "lpjml_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [17] "lpjml_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [18] "lpjml_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
## [19] "lpjml_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [20] "lpjml_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [21] "lpjml_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [22] "lpjml_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [23] "lpjml_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [24] "lpjml_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
## [25] "pcr-globwb_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [26] "pcr-globwb_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [27] "pcr-globwb_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
## [28] "pcr-globwb_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [29] "pcr-globwb_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [30] "pcr-globwb_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [31] "pcr-globwb_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [32] "pcr-globwb_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [33] "pcr-globwb_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
## [34] "vic_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [35] "vic_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [36] "vic_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [37] "vic_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [38] "vic_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [39] "vic_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [40] "vic_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [41] "vic_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [42] "vic_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
```

```r
# Name the slots ------------------------------------------------------------

names(isimip.hist) <- paste(model.names, climate.scenarios, social.scenarios, sep = "/")

# Clean and bind dataset ----------------------------------------------------

isimip.dt <- rbindlist(isimip.hist, idcol = "model") %>%
  na.omit() %>%
  .[, model:= factor(model)] %>%
  .[, c("model", "climate", "social"):= tstrsplit(model, "/")]

fwrite(isimip.dt, "isimip.dt.csv")
```

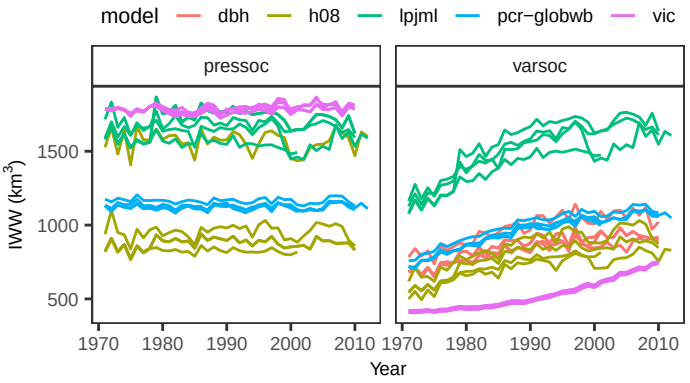
```
# Pressoc: constant human impacts in the form of dams and reservoirs
# varsoc: variable human impacts.
```

2.1.1 Plot data

```
# PLOT ISIMIP ##################################################################

# Continental level ------------------------------------------------------------

isimip.dt[, sum(V1, na.rm = TRUE), .(Continent, model, year, climate, social)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = model,
                linetype = climate)) +
  facet_wrap(social~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme_AP() +
  guides(color = guide_legend(nrow = 2)) +
  guides(linetype = guide_legend(nrow = 2)) +
  theme(legend.position = "top")
```




```
# Global level -----------------------------------------------------------------

isimip.dt[, sum(V1, na.rm = TRUE), .(year, model, climate, social)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = model)) +
  geom_line() +
  facet_wrap(~social) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme_AP() +
  theme(legend.position = "top")
```



2.2 Predictions

```
# RETRIEVE PROJECTIONS FROM ISIMIP ###############################################

# Create vector with list of files ---------------------------------------------

path.projections <- "./files/isimip_future"
list.of.files.projections <- list.files(path.projections)
files.directory.projections <- paste(path.projections, list.of.files.projections, sep = "/")
variable <- "airrww"
start_year <- 2006

# Create parallel cluster ------------------------------------------------------

numCores <- detectCores() * 0.75
cl <- makeCluster(numCores)
registerDoParallel(cl)

# Run for loop -----------------------------------------------------------------

isimip.future <- foreach(i = 1:length(files.directory.projections),
                         .packages = c("data.table", "countrycode", "tidyverse",
                                       "sp", "rworldmap", "ncdf4")) %dopar% {

                                         get_isimip_fun(nc_file = files.directory.projections[i]
                                                        variable = variable,
                                                        start_year = start_year)
                                       }

# Stop the cluster after the computation ---------------------------------------

stopCluster(cl)
```

```
# ARRANGE DATA ###################################################################

# Number of files --------------------------------------------------------------
```

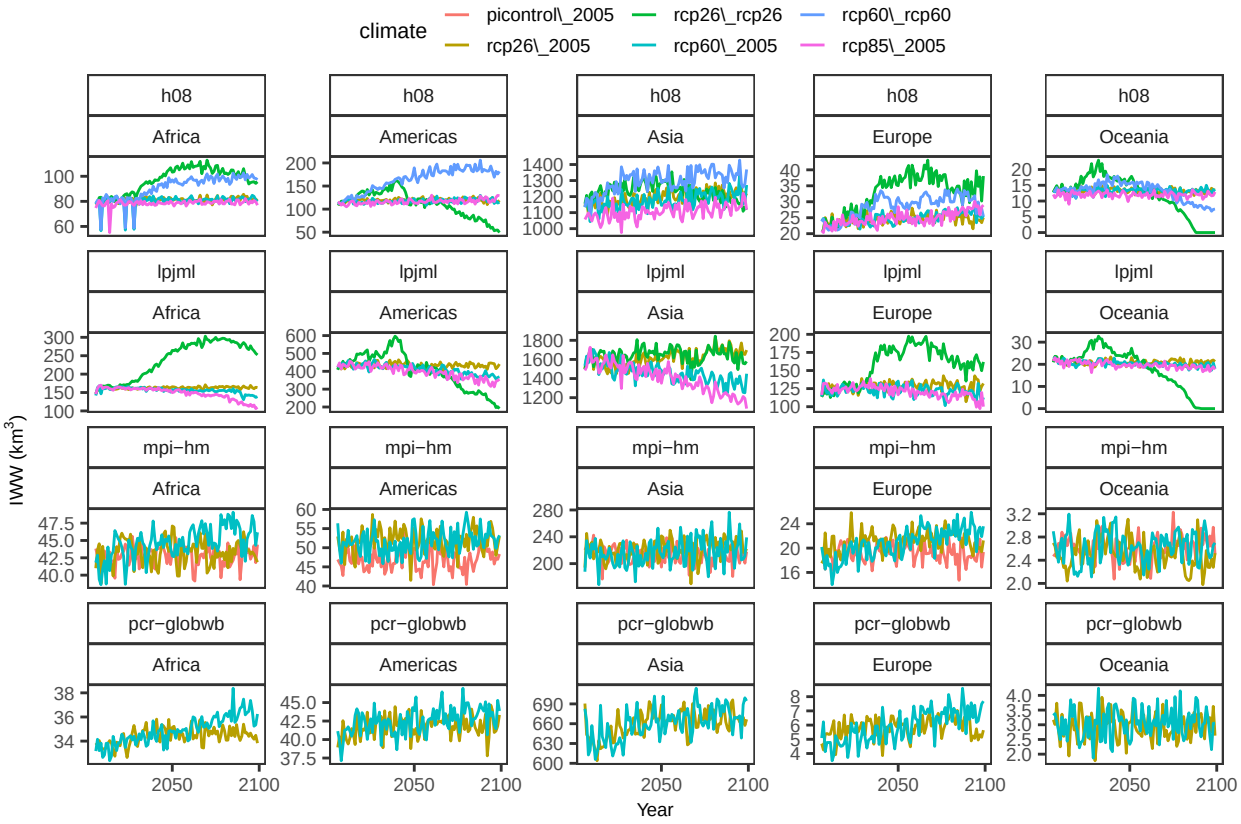
```
list.of.files.projections
```

```
##  [1] "h08_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [2] "h08_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [3] "h08_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [4] "h08_miroc5_ewembi_rcp60_rcp60soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [5] "h08_miroc5_ewembi_rcp85_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [6] "lpjml_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [7] "lpjml_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [8] "lpjml_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [9] "lpjml_miroc5_ewembi_rcp85_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [10] "mpi-hm_miroc5_ewembi_picontrol_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [11] "mpi-hm_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [12] "mpi-hm_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [13] "pcr-globwb_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [14] "pcr-globwb_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
```

```
# Arrange names ------------------------------------------------------------

model.names <- sub("^(.*?)_.*", "\\1", list.of.files.projections)
pattern <- "ewembi_(.*?)soc"
climate <- sub(".*ewembi_(.*?)soc.*", "\\1", list.of.files.projections)
names(isimip.future) <- paste(model.names, climate, sep = "/")

# Clean and bind dataset ---------------------------------------------------

isimip.future.dt <- rbindlist(isimip.future, idcol = "model") %>%
  na.omit() %>%
  .[, model:= factor(model)] %>%
  .[, year:= as.numeric(year)]

isimip.future.dt[, c("model", "climate") := tstrsplit(model, "/")]

# Export -------------------------------------------------------------------

fwrite(isimip.future.dt, "isimip.future.dt.csv")
```

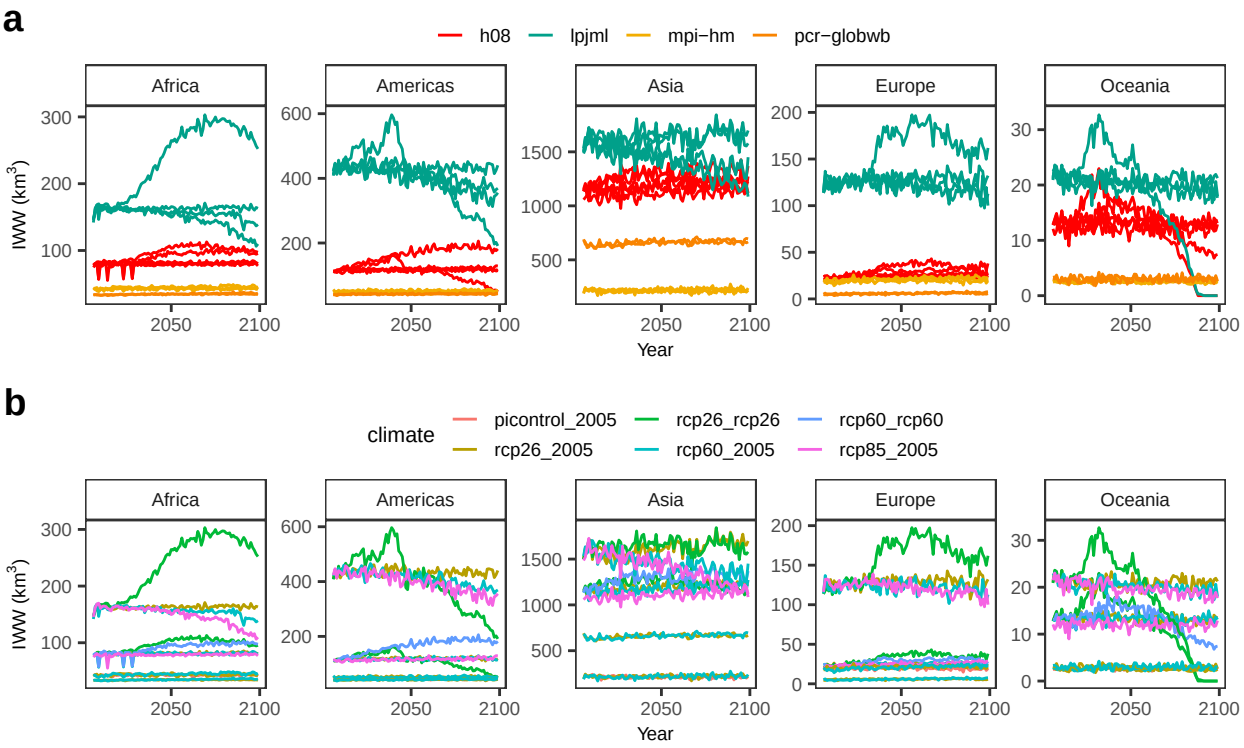
```
# PLOT ISIMIP ##################################################################

# Continental level --------------------------------------------------------

isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate)] %>%
  .[, climate:= gsub("_", "\\\\_", climate)] %>%
  ggplot(., aes(year, V1, group = climate, color = climate)) +
  facet_wrap(model~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme_AP() +
```

```
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme(legend.position = "top")
```




```
# PLOT ISIMIP MERGED ##########################################################

a <- isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = model)) +
  facet_wrap(~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  scale_color_manual(name = "", values = wes_palette(name = selected.palette)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  theme(legend.position = "top")

b <- isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = climate)) +
  facet_wrap(~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  theme(legend.position = "top")
```

```
plot_grid(a, b, ncol = 1, labels = "auto")
```



2.3 ANOVA

```
# ANOVA ###################################################################

# Arrange ISIMIP datasets ------------------------------------------------

isimip.full <- isimip.dt[social == "varsoc"][, context:= "historic"] %>%
  rbind(., isimip.future.dt[, context:= "prediction"], fill = TRUE) %>%
  .[, social:= NULL]

isimip.anova <- isimip.full[, .(estimation = sum(V1)),
                            .(Continent, climate, context, model, year)]

# ARRANGE DATA ############################################################

columns_to_factor <- c("Continent", "climate", "model")
isimip.full[, (columns_to_factor):= lapply(.SD, as.factor), .SDcols = (columns_to_factor)]
isimip.anova[, (columns_to_factor):= lapply(.SD, as.factor), .SDcols = (columns_to_factor)]

# RUN MODEL AND ANALYSIS OF VARIANCE ######################################

# List of models ---------------------------------------------------------

functions <- list(lmm = lmm_fun,
```

```
                  gamm = gamm_fun,
                  rf = rf_fun,
                  bayes = bayes_fun)

# Apply each function to the data and combine results --------------------------

results <- mclapply(names(functions), function(fun_name) {

  isimip.anova[, functions[[fun_name]](.SD), .(Continent, context)]

},
mc.cores = detectCores() * 0.75)
```

```
# PLOT RESULTS ###############################################################

results
```

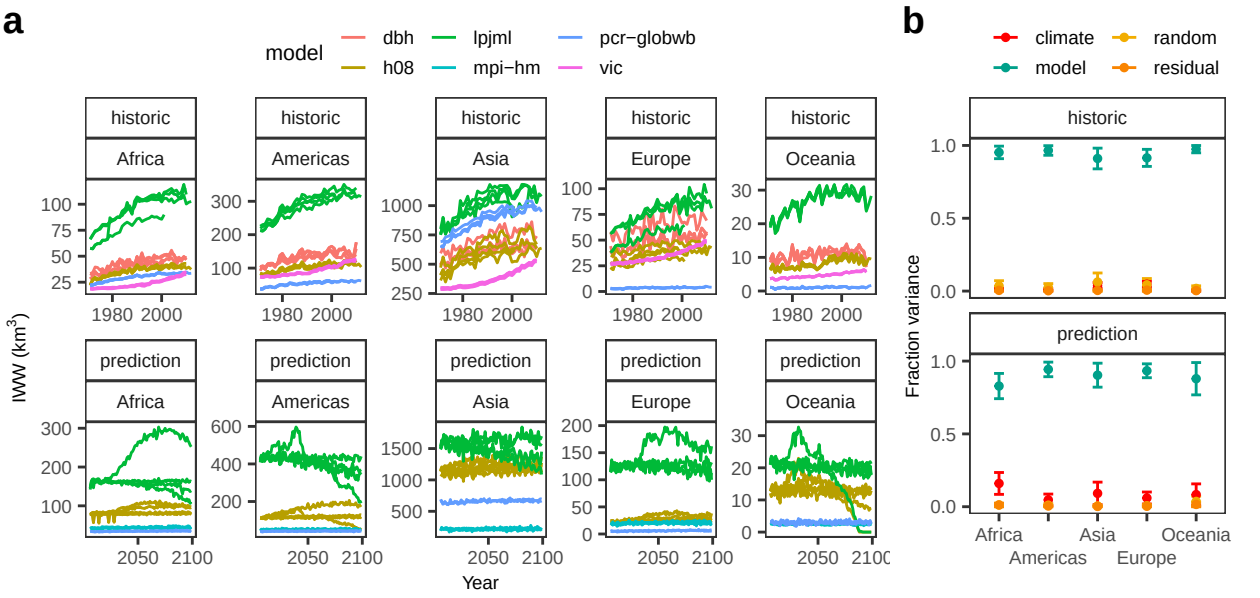
```
## [[1]]
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##  1:      Asia   historic     0.0182441856      0.9815439    1.604121e-04
##  2:    Europe   historic     0.0265735831      0.9732386    7.928135e-05
##  3:    Africa   historic     0.0046293623      0.9952289    7.974990e-05
##  4:  Americas   historic     0.0015875370      0.9983346    4.897266e-05
##  5:   Oceania   historic     0.0003011393      0.9996366    2.836314e-05
##  6:      Asia prediction     0.0144443043      0.9855396    1.802974e-21
##  7:    Europe prediction     0.0188199322      0.9811568    9.455137e-07
##  8:    Africa prediction     0.0847272814      0.9151935    1.015636e-22
##  9:  Americas prediction     0.0070916322      0.9928739    2.351915e-06
## 10:   Oceania prediction     0.0099009112      0.9899272    2.436002e-05
##     residual_variance
##                 <num>
##  1:      5.146166e-05
##  2:      1.085044e-04
##  3:      6.196443e-05
##  4:      2.885478e-05
##  5:      3.387542e-05
##  6:      1.606501e-05
##  7:      2.232385e-05
##  8:      7.922237e-05
##  9:      3.208885e-05
## 10:      1.475610e-04
##
## [[2]]
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##  1:      Asia   historic     0.0582396865      0.9326743    3.492825e-06
##  2:    Europe   historic     0.0665137789      0.9204392    2.795270e-04
```

```
##  3:    Africa   historic     0.0058233555      0.9841575    3.265345e-04
##  4:  Americas   historic     0.0027474682      0.9923858    3.009048e-05
##  5:   Oceania   historic     0.0004492087      0.9905800    2.549049e-03
##  6:      Asia prediction     0.0233855736      0.9728348    1.274156e-10
##  7:    Europe prediction     0.0472909695      0.9462095    8.071134e-05
##  8:    Africa prediction     0.1977722547      0.7786924    6.947724e-05
##  9:  Americas prediction     0.0228104251      0.9679342    9.751115e-06
## 10:   Oceania prediction     0.0213692004      0.9437060    3.414224e-03
##     residual_variance
##                 <num>
##  1:       0.009082472
##  2:       0.012767490
##  3:       0.009692578
##  4:       0.004836623
##  5:       0.006421754
##  6:       0.003779619
##  7:       0.006418860
##  8:       0.023465907
##  9:       0.009245593
## 10:       0.031510534
##
## [[3]]
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##  1:      Asia   historic       0.03651589      0.8392607      0.12421897
##  2:    Europe   historic       0.05732503      0.8561269      0.08615885
##  3:    Africa   historic       0.01925291      0.9091631      0.07124754
##  4:  Americas   historic       0.01621633      0.9325713      0.05118237
##  5:   Oceania   historic       0.01243839      0.9494631      0.03595673
##  6:      Asia prediction       0.16884042      0.8208680      0.01029125
##  7:    Europe prediction       0.10083726      0.8857703      0.01334813
##  8:    Africa prediction       0.23492099      0.7417898      0.02324906
##  9:  Americas prediction       0.08681625      0.8927305      0.02044727
## 10:   Oceania prediction       0.15674244      0.7680757      0.07252973
##     residual_variance
##                 <lgcl>
##  1:                NA
##  2:                NA
##  3:                NA
##  4:                NA
##  5:                NA
##  6:                NA
##  7:                NA
##  8:                NA
##  9:                NA
## 10:                NA
##
## [[4]]
```

```
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##  1:      Asia   historic     0.0585877490      0.9114970    2.307509e-02
##  2:    Europe   historic     0.0679479627      0.9104088    9.472626e-03
##  3:    Africa   historic     0.0069267842      0.9713291    1.254960e-02
##  4:  Americas   historic     0.0030365269      0.9846379    7.963846e-03
##  5:   Oceania   historic     0.0003067787      0.9899282    4.641493e-03
##  6:      Asia prediction     0.0233300054      0.9728583    1.131701e-05
##  7:    Europe prediction     0.0469288511      0.9463859    2.596976e-04
##  8:    Africa prediction     0.1977676855      0.7778277    5.262552e-05
##  9:  Americas prediction     0.0228624389      0.9669629    7.071621e-04
## 10:   Oceania prediction     0.0208228448      0.9423662    5.325046e-03
##     residual_variance
##                 <num>
##  1:       0.006840208
##  2:       0.012170596
##  3:       0.009194540
##  4:       0.004361695
##  5:       0.005123568
##  6:       0.003800369
##  7:       0.006425531
##  8:       0.024351981
##  9:       0.009467473
## 10:       0.031485861
```

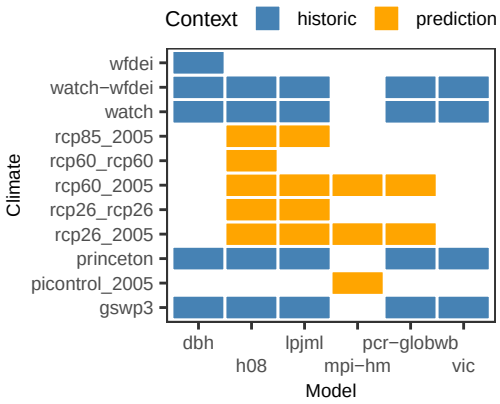
```
results.dt <- rbindlist(results)

a <- isimip.full[, .(estimation = sum(V1)), .(model, Continent, climate, year, context)] %>%
  ggplot(., aes(year, estimation, color = model, group = interaction(climate, model))) +
  geom_line() +
  facet_wrap(context~Continent, scale = "free", ncol = 5) +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  guides(colour = guide_legend(nrow = 2)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme(legend.position = "top",
        legend.box.spacing = unit(0, "pt"))

b <- results.dt %>%
  melt(., measure.vars = c("climate_variance", "model_variance", "random_variance",
                           "residual_variance")) %>%
  .[, .(min = min(value, na.rm = TRUE),
        max = max(value, na.rm = TRUE)), .(Continent, context, variable)] %>%
  .[, variance:= tstrsplit(variable, "_", fixed = TRUE)[[1]]] %>%
  ggplot(., aes(x = Continent, ymin = min, ymax = max, y = (min + max) / 2, color = variance)) +
  geom_errorbar(width = 0.2) +
  geom_point(size = 1) +
  scale_color_manual(name = "", values=wes_palette(selected.palette, n = 4)) +
```

```
  labs(x = "", y = "Fraction variance") +
  facet_wrap(~context, ncol = 1) +
  theme(legend.position = "top") +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  theme(legend.position = "top") +
  guides(color = guide_legend(nrow = 2)) +
  theme(legend.position = "top") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2))

plot_grid(a, b, ncol = 2, labels = "auto", rel_widths = c(0.72, 0.28))
```




```
# COUNT COMBINATIONS OF MODEL AND CLIMATE ########################################

unique(isimip.full[, .(model, climate, context)]) %>%
  ggplot(., aes(x = model, y = climate, fill = context)) +
  geom_tile(color = "white", size = 0.5) +
  scale_fill_manual(values = c("historic" = "steelblue", "prediction" = "orange")) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Model", y = "Climate", fill = "Context") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "top")
```

```
## Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
## i Please use `linewidth` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see where this warning was
## generated.
```



3 Khan et al dataset

```
# KHAN ET AL 2023 DATASET ##############################################################

path.projections <- "./files/khan_et_al_2023"
list.of.files <- list.files(path.projections, pattern = "\\.csv$")
combinations <- lapply(list.of.files, function(x) strsplit(x, "_")[[1]][1:4]) %>%
  do.call(rbind, .) %>%
  data.frame()
colnames(combinations) <- c("SSP", "RCP", "Climate", "Use")

# READ FILES IN PARALLEL ###############################################################

# Create parallel cluste -----------------------------------------------------

numCores <- detectCores() * 0.75
cl <- makeCluster(numCores)
registerDoParallel(cl)

# Run for loop ---------------------------------------------------------------

result <- foreach(i = 1:length(list.of.files),
                  .combine = "rbind",
                  .packages = c("data.table", "countrycode",
                                "sp", "rworldmap")) %dopar% {

                                  out <- fread(paste("./files/khan_et_al_2023/", list.of.files
                                  out[, `:=`(SSP = combinations[i, 1],
                                             RCP = combinations[i, 2],
                                             Climate = combinations[i, 3],
                                             Use = combinations[i, 4])]

                                  Country <- coords2country(out[1:nrow(out), 2:3])

                                  df <- cbind(Country, out)
```

```
                                df[, Continent := countrycode(Country, origin = "country.name

                                df[, Dataset := list.of.files[i]]

                                df
                              }

# Stop the cluster after the computation -------------------------------------

stopCluster(cl)
```

```
# ARRANGE DATA ###############################################################

numeric_cols <- grep("^[0-9]+$", names(result), value = TRUE)
khan.dt <- melt(result, measure.vars = numeric_cols, variable.name = "Year") %>%
  .[, Year:= as.numeric(as.character(Year))] %>%
  .[, model:= "GCAM"] %>%
  na.omit()

# EXPORT DATA ################################################################

khan.dt.continent <- khan.dt[, .(estimation = sum(value)),
                             .(Year, Continent, Use, RCP, SSP, Climate, Dataset, model)] %>%
  .[, climate:= paste(Climate, RCP, SSP, sep = "_")]

fwrite(khan.dt.continent, "khan.dt.continent.csv")
```

```
# PLOT ########################################################################

# Continental ----------------------------------------------------------------

plot.khan.continental <- khan.dt.continent %>%
  ggplot(., aes(Year, estimation, color = Continent, group = interaction(Dataset, Continent)))
  geom_line(alpha = 0.3) +
  facet_wrap(~Use) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "", y = bquote("km"^3))

plot.khan.continental
```

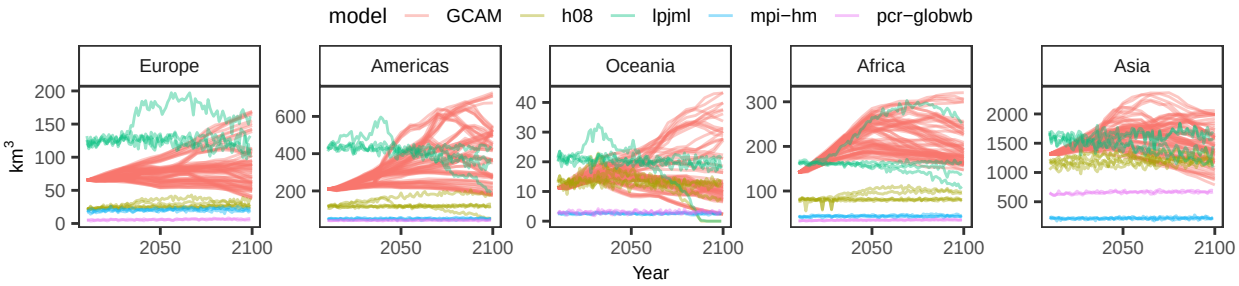
```
# PLOT ########################################################################

# Global ---------------------------------------------------------------------

plot.khan.global <- khan.dt[, sum(value), .(Year, Use, Dataset)] %>%
  ggplot(., aes(Year, V1, group = Dataset)) +
  geom_line(alpha = 0.3) +
```

```
  facet_wrap(~Use) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))

plot.khan.global
```

```
# MERGE KHAN ET AL DATASETS ############################################################

plot_grid(plot.khan.continental, plot.khan.global, ncol = 1, labels = "auto",
          rel_heights = c(0.53, 0.47))
```

```
# PLOT SSPS VS RCPS ####################################################################

khan.dt[, sum(value), .(Year, Use, Dataset, RCP, SSP)] %>%
  ggplot(., aes(Year, V1, group = Dataset, color = Use)) +
  geom_line() +
  facet_grid(RCP~SSP) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))
```

```
# MERGE KHAN ET AL DATA WITH ISIMIP ####################################################

# Arrange data ---------------------------------------------------------------------

khan.dt.continent <- fread("khan.dt.continent.csv")

khan.dt2 <- khan.dt.continent[Use == "withdrawals", .(model, Continent, climate, Year, estimati
  setnames(., "Year", "year")

# Extract prediction data from ISIMIP ----------------------------------------------

isimip.full2 <- isimip.full[context == "prediction" & year >= 2010,
            .(estimation = sum(V1)), .(model, Continent, climate, year, context)] %>%
  .[, context:= NULL]

# Merge and plot -------------------------------------------------------------------

merged.dt <- rbind(khan.dt2, isimip.full2)

ggplot(merged.dt, aes(year, estimation, group = interaction(climate, model), color = model)) +
  geom_line(alpha = 0.4) +
  facet_wrap(~Continent, scale = "free_y", ncol = 5) +
  theme_AP() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))
```




```
# Calculate the min and max in 2030-2050 given uncertainty and the global level -----

merged.dt[year %in% c(2030, 2040, 2050),
          .(min = min(estimation), max = max(estimation)), .(Continent, year)] %>%
  .[, .(sum_min = sum(min), sum_max = sum(max)), year]
```

```
##    year  sum_min  sum_max
## 1: 2030 272.8320 2529.235
## 2: 2040 281.8063 2958.560
## 3: 2050 278.4169 3188.283
```

4 Bibliographical study

```
# NAOMI DATASET ################################################################

references.projected <- data.table(read.xlsx("./data/references_projection.xlsx")) %>%
  .[, focus:= "projected"]

references.current <- data.table(read.xlsx("./data/references_current.xlsx")) %>%
  .[, focus:= "current"]

references.full.dt <- rbind(references.projected, references.current) %>%
  .[, study:= paste(author, model, climate.scenario, sep = ".")]

# CLEAN THE DATASET ############################################################

colnames_vector <- c("title", "author", "region")

# Remove leading and trailing spaces -----------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, trimws), .SDcols = (colnames_vector)]
references.full.dt[, (colnames_vector):= lapply(.SD, str_squish), .SDcols = (colnames_vector)]

# Lowercaps ------------------------------------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, tolower), .SDcols = (colnames_vector)]

# Remove multiple spaces -----------------------------------------------------
```

```r
references.full.dt[, (colnames_vector):= lapply(.SD, function(x)
  gsub("\\s+", " ", x)), .SDcols = (colnames_vector)]

# Correct America ------------------------------------------------------------

references.full.dt[, region:= ifelse(region == "america", "americas", region)]

# Extract the publication year -----------------------------------------------

references.full.dt[, publication.date:= str_extract(author, "\\d{4}")] %>%
  .[, publication.date:= as.numeric(publication.date)]
```

```r
# FEATURES OF THE DATASET ####################################################

# Name of different studies --------------------------------------------------

sort(unique(references.full.dt$title))
```

```
##  [1] "a global hydrological simulation to specify the sources of water used by humans"
##  [2] "a global water scarcity assessment under shared socio-economic pathways - part 2: wate
##  [3] "a pathway of global food supply adaptation in a world with increasingly constrained gr
##  [4] "agricultural green and blue water consumption and its influence on the global water sy
##  [5] "agriculture, bioenergy, and water implications of constrained cereal trade and climate
##  [6] "an estimation of global virtual water flow and sources of water withdrawal for major c
##  [7] "an integrated assessment of global and regional water demands for electricity generati
##  [8] "an interpreted model for the assessment of global water resources - part 2: applicatio
##  [9] "appraisal and assessment of world water resources"
## [10] "aquastat: fao's global information system on water and agriculture"
## [11] "climate change impacts on irrigation water requirements: effects of mitigation, 1990-2
## [12] "climate impacts on global irrigation requirements under 19 gcms, simulated with a vege
## [13] "climate policy implications for agricultural water demand"
## [14] "cooling water sufficiency in a warming world: projection using an integrated assessmen
## [15] "future long-term changes in global water resources driven by socio-economic and climat
## [16] "global and regional evaluation of energy for water"
## [17] "global impacts of conversions from natural to agricultural ecosystems on water resourc
## [18] "global irrigation characteristics and effects simulated by fully coupled land surface
## [19] "global irrigation water demand: variability and uncertainties arising from agricultura
## [20] "global modeling of irrigation water requirements"
## [21] "global monthly sectoral water use for 2010-2100 at 0.5° resolution across alternative
## [22] "global water demand and supply projections"
## [23] "globwat - a global water balance model to assess water use in irrigated agriculture"
## [24] "groundwater use for irrigation- a global inventory"
## [25] "how can we cope with the water resources situation by the year 2050?"
## [26] "human appropriation of renewable fresh water"
## [27] "human water consumption intensifies hydrological drought worldwide"
## [28] "human-induced changes in the global water cycle"
## [29] "impact of climate change and variability on irrigation reqirements: a global perspecti
## [30] "impact of climate forcing uncertainty and human water use on global and continental wa
```

```
## [31] "impact of water withdrawals from groundwater and surface water on continental water st
## [32] "implementation and evaluation of irrigation techniques in the community land model"
## [33] "incorporating anthropogenic water regulation modules into a land surface model"
## [34] "incorporation of groundwater pumping in a global land surface model with the represent
## [35] "isimip database"
## [36] "long-term global water projections using six socioeconomic scenarios in an intgrated a
## [37] "modelling global water stress of the recent past: on the relative importance of trends
## [38] "multimodel projections and uncertainties of irrigation water demand under climate char
## [39] "pcr-globwb 2: a 5 arcmin global hydrological and water resources model"
## [40] "physical impacts of climate change on water resources"
## [41] "planetary boundaries: guiding human development on a changing planet"
## [42] "present-day irrigation mitigares heat extremes"
## [43] "projected water consumption in future global agriculture: scenarios and related impact
## [44] "projection of future world water resources under sres scenarios: water withdrawal"
## [45] "recent global cropland water consumption constrained by observations"
## [46] "reconciling irrigated food production with environmental flows for sustainable develop
## [47] "reconstructing 20th century global hydrography: a contribution to the global terrestri
## [48] "reconstructing 20th century global hydrography: a contribution to the global terrestri
## [49] "sustainability of global water use: past reconstruction and future projections"
## [50] "the number of people exposed to water stress in relation to how much water is reserved
## [51] "the state of the world's land and water resources for food and agriculture"
## [52] "the world’s water, 2000-2001: the biennial report on freshwater resources"
## [53] "united nations world water development report 2020: water and climate change"
## [54] "water 2050. moving toward a sustainable vision fot the earth's fresh water"
## [55] "water and sustainability: a global outlook"
## [56] "water and sustainability. global pattern and long-range problems"
## [57] "water resources for sustainable development"
## [58] "water sector assumptions for the shared socioeconomic pathways in an integrated model
## [59] "world agriculture towards 2030/2050"
## [60] "world agriculture towards 2030/2050: the 2012 revision"
## [61] "world agriculture towards 2030/2053"
## [62] "world agriculture towards 2030/2054"
## [63] "world agriculture towards 2030/2055"
## [64] "world water demand and supply, 1990 to 2025: scenarios and issues"
## [65] "world water in 2025 - global modeling and scenario analysis for the world commission o
## [66] "world water resources and their future"
## [67] "world water resources and water use: modern assessment and outlook for future"
```

```
# Number of data points ------------------------------------------------------

nrow(references.full.dt)
```

```
## [1] 1866
```

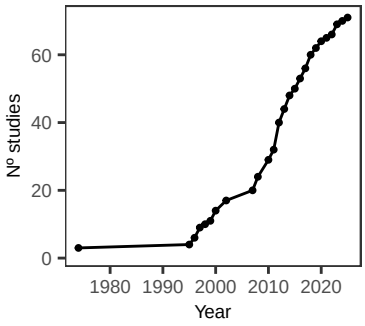
```
# Name of different studies per variable -------------------------------------

references.full.dt[, unique(title), variable] %>%
  .[, .N, variable]
```

```
##    variable  N
## 1:      iww 41
## 2:      tww 34
## 3:      iwc 19
## 4:      twc  7
## 5:      iwr  3
```

```
# Cumulative sum of published studies ----------------------------------------

dt <- references.full.dt[, .(title, publication.date)] %>%
  .[!duplicated(.)] %>%
  setorder(., publication.date) %>%
  .[, .N, publication.date] %>%
  .[, cumulative_sum := cumsum(N)]

ggplot(dt, aes(publication.date, cumulative_sum)) +
  geom_line() +
  geom_point(size = 0.7) +
  theme_AP() +
  labs(x = "Year", y = "Nº studies")
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
```

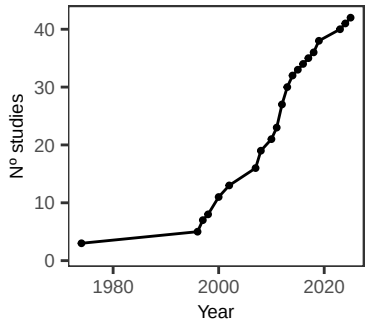
```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```



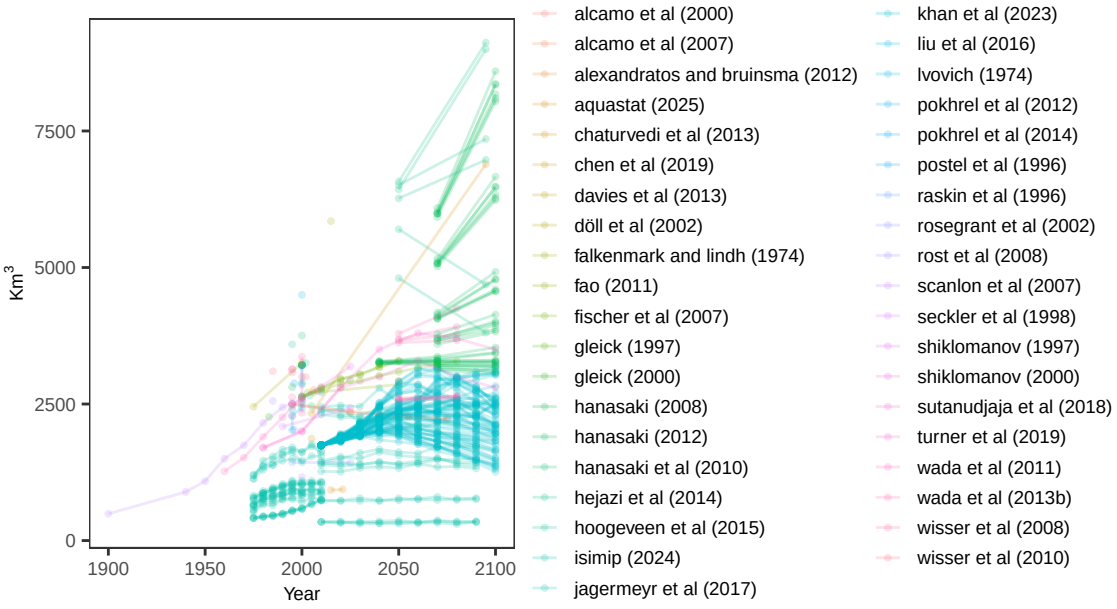

```
# Only irrigation water withdrawal studies -----------------------------------

cumulative.iww <- references.full.dt[, .(title, publication.date, variable)] %>%
  .[variable == "iww"] %>%
  .[!duplicated(.)] %>%
  setorder(., publication.date) %>%
  .[, .N, publication.date] %>%
  .[, cumulative_sum := cumsum(N)] %>%
  ggplot(., aes(publication.date, cumulative_sum)) +
  geom_line() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  geom_point(size = 0.7) +
  theme_AP() +
```

```
  labs(x = "Year", y = "Nº studies")

cumulative.iww
```

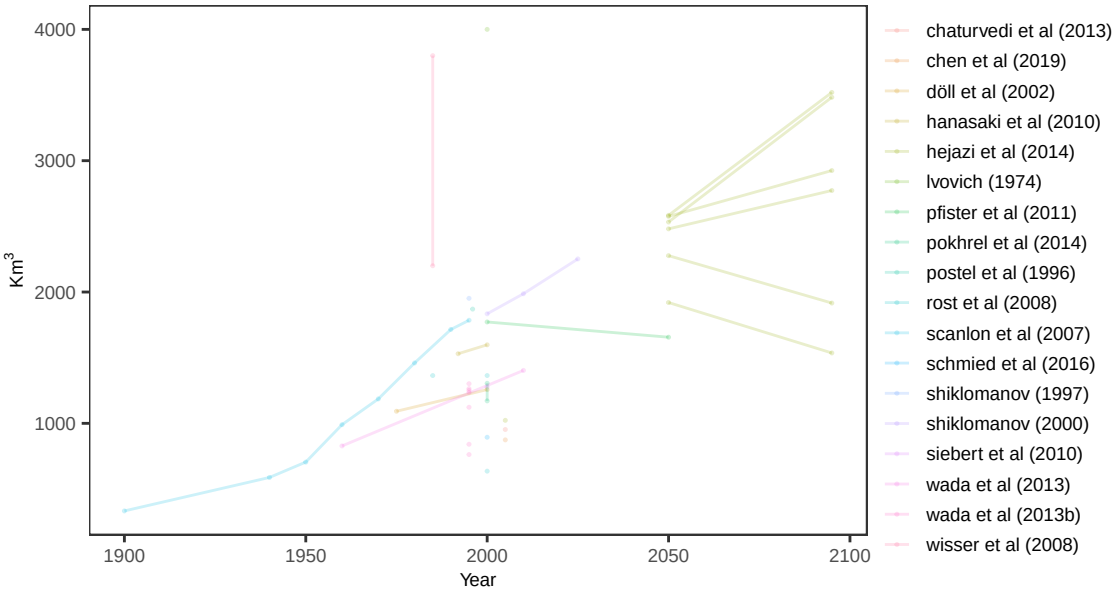
```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
## Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```




```
# PLOT ALL ESTIMATIONS ###########################################################

def.alpha <- 0.2

plot.iww <- references.full.dt[variable == "iww" & region == "global"] %>%
  .[, .(author, study, estimation.year, value)] %>%
  na.omit() %>%
  ggplot(., aes(estimation.year, value, color = author, group = study)) +
  geom_point(alpha = def.alpha, size = 0.7) +
  labs(x = "Year", y = bquote("Km"^3)) +
  scale_color_discrete(name = "") +
  geom_line(alpha = def.alpha) +
  theme_AP()

plot.iww
```



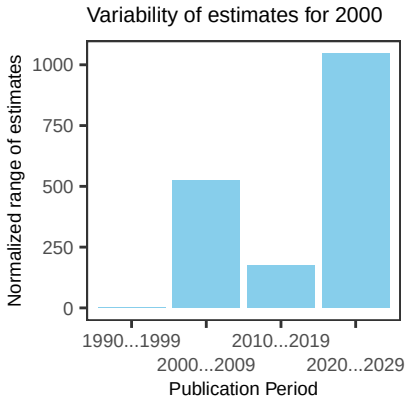

```
references.full.dt[variable == "iwc" & region == "global"] %>%
  .[, .(author, study, estimation.year, value)] %>%
  na.omit() %>%
  ggplot(., aes(estimation.year, value, color = author, group = study)) +
  geom_point(alpha = def.alpha, size = 0.2) +
  labs(x = "Year", y = bquote("Km"^3)) +
  scale_color_discrete(name = "") +
  geom_line(alpha = def.alpha) +
  theme_AP()
```



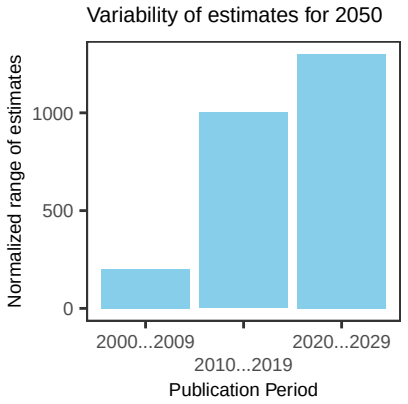
4.1 Evolution of uncertainty through time

```r
# RUN FUNCTION ########################################################################

years_interest <- c(2000, 2050)

plot.years <- lapply(years_interest, function(year)
  evolution_uncertainty_fun(data = references.full.dt, target_year = year))

plot.years
```

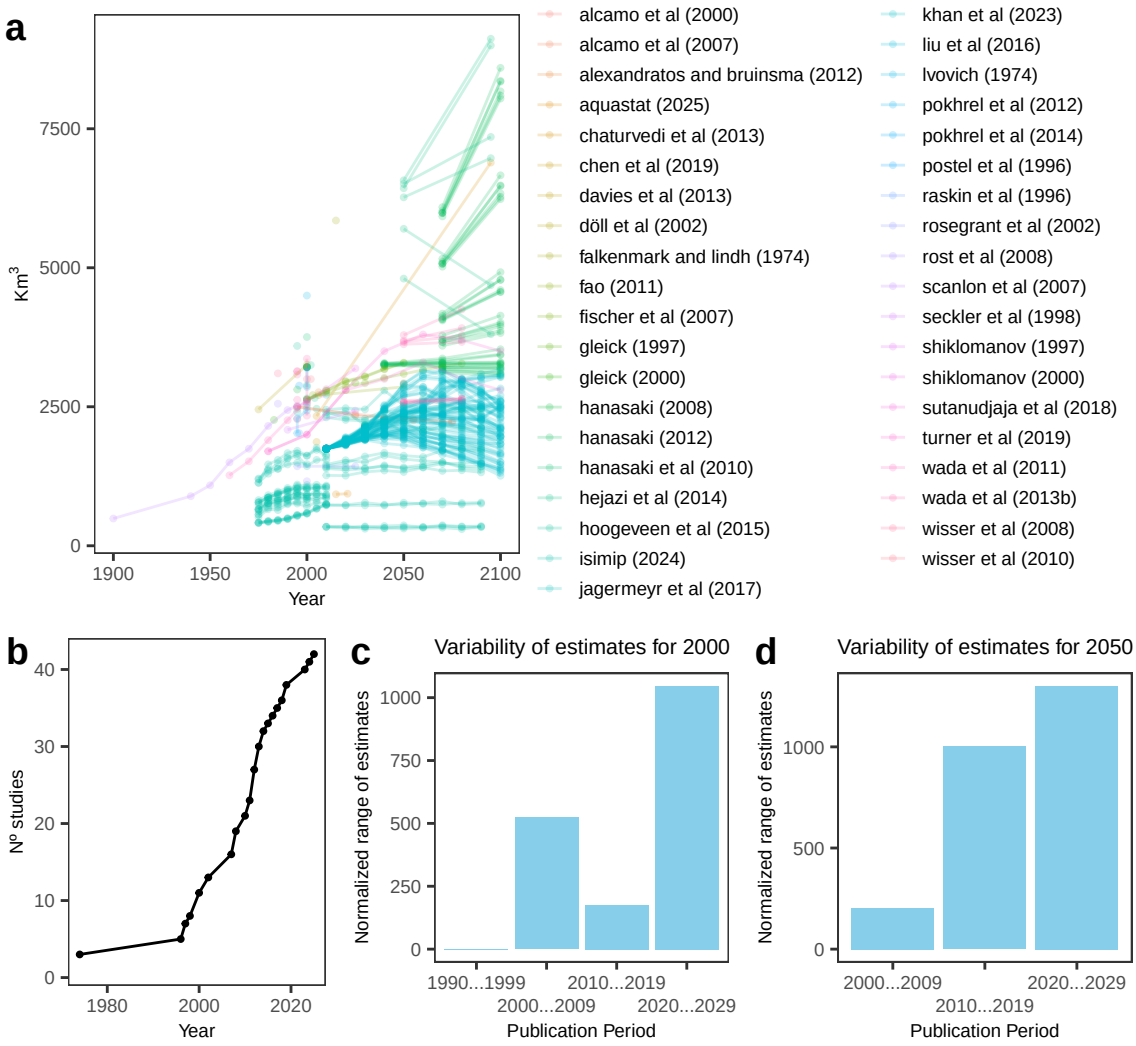
```
## [[1]]
```




```
##
## [[2]]
```




```r
bottom <- plot_grid(cumulative.iww, plot.years[[1]], plot.years[[2]], ncol = 3,
                    labels = c("b", "c", "d"), rel_widths = c(0.3, 0.35, 0.35))
plot_grid(plot.iww, bottom, ncol = 1, labels = c("a", ""), rel_heights = c(0.65, 0.45))
```


a
7500
5000
2500
0
Km3
1900
1950
2000
2050
2100
Year
alcamo et al (2000)
alcamo et al (2007)
alexandratos and bruinsma (2012)
aquastat (2025)
chaturvedi et al (2013)
chen et al (2019)
davies et al (2013)
döll et al (2002)
falkenmark and lindh (1974)
fao (2011)
fischer et al (2007)
gleick (1997)
gleick (2000)
hanasaki (2008)
hanasaki (2012)
hanasaki et al (2010)
hejazi et al (2014)
hoogeveen et al (2015)
isimip (2024)
jagermeyr et al (2017)
khan et al (2023)
liu et al (2016)
lvovich (1974)
pokhrel et al (2012)
pokhrel et al (2014)
postel et al (1996)
raskin et al (1996)
rosegrant et al (2002)
rost et al (2008)
scanlon et al (2007)
seckler et al (1998)
shiklomanov (1997)
shiklomanov (2000)
sutanudjaja et al (2018)
turner et al (2019)
wada et al (2011)
wada et al (2013b)
wisser et al (2008)
wisser et al (2010)
b
40
30
20
10
0
Nº studies
1980
2000
2020
Year
c
Variability of estimates for 2000
1000
750
500
250
0
Normalized range of estimates
1990...1999
2000...2009
2010...2019
2020...2029
Publication Period
d
Variability of estimates for 2050
1000
500
0
Normalized range of estimates
2000...2009
2010...2019
2020...2029
Publication Period

5 Session information

```
# SESSION INFORMATION ############################################################

sessionInfo()
```

```
## R version 4.3.3 (2024-02-29)
## Platform: aarch64-apple-darwin20 (64-bit)
## Running under: macOS Sonoma 14.2.1
##
## Matrix products: default
## BLAS:   /Library/Frameworks/R.framework/Versions/4.3-arm64/Resources/lib/libRblas.0.dylib
## LAPACK: /Library/Frameworks/R.framework/Versions/4.3-arm64/Resources/lib/libRlapack.dylib;
##
## locale:
## [1] en_US.UTF-8/en_US.UTF-8/en_US.UTF-8/C/en_US.UTF-8/en_US.UTF-8
##
## time zone: Europe/London
## tzcode source: internal
##
## attached base packages:
## [1] parallel  stats     graphics  grDevices utils     datasets  methods
## [8] base
##
## other attached packages:
##  [1] microbenchmark_1.5.0 lme4_1.1-35.5        Matrix_1.6-5
##  [4] here_1.0.1           doParallel_1.0.17    iterators_1.0.14
##  [7] foreach_1.5.2        rworldmap_1.3-8      sp_2.1-4
## [10] countrycode_1.6.0    ncdf4_1.23           scales_1.3.0
## [13] wesanderson_0.3.7    benchmarkme_1.0.8    cowplot_1.1.3
## [16] lubridate_1.9.3      forcats_1.0.0        stringr_1.5.1
## [19] dplyr_1.1.4          purrr_1.0.2          readr_2.1.5
## [22] tidyr_1.3.1          tibble_3.2.1         ggplot2_3.5.1
## [25] tidyverse_2.0.0      data.table_1.16.2    openxlsx_4.2.7.1
##
## loaded via a namespace (and not attached):
##  [1] dotCall64_1.2         benchmarkmeData_1.0.4 gtable_0.3.6
##  [4] spam_2.11-0           xfun_0.49             raster_3.6-30
##  [7] lattice_0.22-6        tzdb_0.4.0            Rdpack_2.6.2
## [10] vctrs_0.6.5           tools_4.3.3           generics_0.1.3
## [13] fansi_1.0.6           pkgconfig_2.0.3       lifecycle_1.0.4
## [16] compiler_4.3.3        fields_16.3           munsell_0.5.1
## [19] terra_1.7-78          codetools_0.2-20      htmltools_0.5.8.1
## [22] maps_3.4.2.1          yaml_2.3.10           nloptr_2.1.1
## [25] pillar_1.9.0          MASS_7.3-60.0.1       boot_1.3-31
## [28] nlme_3.1-166          tidyselect_1.2.1      zip_2.3.1
## [31] digest_0.6.37         stringi_1.8.4         splines_4.3.3
## [34] sensobol_1.1.5        rprojroot_2.0.4       fastmap_1.2.0
```

```
## [37] grid_4.3.3            colorspace_2.1-1      cli_3.6.3
## [40] magrittr_2.0.3        utf8_1.2.4            withr_3.0.2
## [43] timechange_0.3.0      rmarkdown_2.29        httr_1.4.7
## [46] hms_1.1.3             evaluate_1.0.1        knitr_1.49
## [49] rbibutils_2.3         viridisLite_0.4.2     rlang_1.1.4
## [52] Rcpp_1.0.13-1         glue_1.8.0            minqa_1.2.8
## [55] rstudioapi_0.17.1     R6_2.5.1
```

```
## Return the machine CPU ------------------------------------------------------

cat("Machine:     "); print(get_cpu()$model_name)
```

```
## Machine:

## [1] "Apple M1 Max"
```

```
## Return number of true cores -------------------------------------------------

cat("Num cores:   "); print(detectCores(logical = FALSE))
```

```
## Num cores:

## [1] 10
```

```
## Return number of threads ----------------------------------------------------

cat("Num threads: "); print(detectCores(logical = FALSE))
```

```
## Num threads:

## [1] 10
```