Water Availability in Snow Dominated Regions under Projected Climatic Variability

A Case Study of Alpine Catchment, Austria

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Abstract—**This study analyzes the response of various hydrological parameters and future water availability against anticipated climate variations in snow dominated alpine catchment in Austria. The parameters assessed are base flow, environmental flow, total flow, evapotranspiration, and snow cover duration. The distributed hydrological modeling system PREVAH is developed to assess the impacts through the combination of various climate change scenarios produced under the framework of the European project PRUDENCE. The model results clearly indicate an apparent shift from observed trends in monthly, seasonal and annual values. The mean annual changes observed by all model scenarios range between 45% to 60% decrease in snow cover duration, 15% to 20% increase in evapotranspiration, 5% to 15% decrease in base flow, and 15% to 25% decrease in total runoff values. However, mean annual changes observed in available water are marginal, just ranging from -3% to +2%. All regional model projections show more or less the same identical pattern of changes in analyzed parameters.**

Keywords-climate change; Alpine catchment; hydrological response; water availability

I. Introduction

The mid-20th century, considered as an era of industrialization, has led to unprecedented use of fossil fuels which are a major cause for releases of anthropogenic greenhouse gases [1]. The clear-cut outcome is ever increasing temperature. The increasing temperature trend is a main catalyst behind change in climatic parameters. These changes have exhibited far-reaching effects on man and its eco-system. In [1], authors concluded that warming of the earth's atmosphere is unambiguous and since the mid of the 19th century, the last three decades are the warmest ones at the earth's surface than any preceding ones. The 30 year period from 1983-2012 is probably the hottest one in the last 14 centuries. They also reported a 0.85°C global temperature rise since 1880s [1]. However, the change in mountain regions is almost three times higher than the 20th century global average. Similar trend is observed in European Alps, a major supply source of 4 Alpine rivers: Danube, Rhine, Rhone and Po. Therefore, the region is considered highly prone to climatic variations [2]. These variations may affect region's hydrological cycle. Several researchers already concluded that climatic variability alters the snow storage which subsequently affects timing and flow volumes in alpine catchments. Anticipated seasonality change may also bring severe complications for adjacent lowland areas [3-7]. Furthermore, it may affect constant water availability, hydropower generation, water tourism etc. Numerous other studies are also not only raising concerns over reliability of water supply sources but also acknowledge severe complications for water management systems [4, 8]. In such context, the present study analyzes catchment flow component's sensitivity towards future climate change scenarios and subsequent impact on water availability. The hydrological modeling system PREVAH is developed to analyze mean flow, low flow (Q95) and base flow changes. Most of the studies generally investigate the climate variation effect on average flow conditions. However, there is a possibility that variation may not affect average flow conditions but may affect low flow conditions. Hence, may affect reliability of water supply sources. Similarly the temporal and spatial patterns (in raster format) of base flow analysis would indicate total water available for infiltration to, or abstraction from the ground water system. The findings will benefit the protection of ground water resources, land use allocation and development, and future water resource planning and management.

II. Study area

The study is conducted over Kitzbüheler Ache catchment located in region of north-eastern Alps, Austria. The catchment is non-glacierized and its elevation ranges from 600m to 2400m, with mean level of 1291m. It encompasses an area of about 323km^2. The average annual precipitation varies from 1474mm to 1784mm, with peaks receiving much higher precipitation than valleys. Similarly, high altitude areas remain more (5-7 months) under snow cover than valley areas (2-4 months) [2]. Flow characteristics of the catchment can be distinguished as high flows in spring and early summer due to melting contribution and low flows in winter due to snow accumulation. The average winter runoff is just one-third of summer runoff (392mm). One-third of total precipitation evapo-transpirates, the rest emerges as total runoff. Almost half of the studied area (catchment) is covered by forest. High altitudinal areas are covered with alpine meadows, while low altitudes are covered with pastures. Urban area occupies very small percentage and is confined to the valleys. Mountain tops are covered with bare rocks.

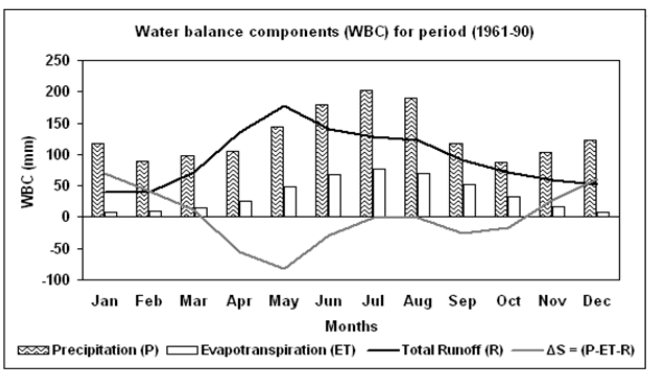

Fig. 1. Average catchment (1961-90), monthly water balance components

III. Climate change scenario development

Generally hydro-climatic studies are based on atmosphere-ocean general circulation model (AO-GCM) projections. These models simulate realistic climate projections. However, at regional scale, its course resolution and limited physical representation produce higher uncertainty and lack the detailed spatial structure of climatic parameters. These issues drastically limit its application in qualitative, detailed assessment of climate change studies at regional level [9]. To satisfy the need to have such detailed information and certainty in future climatic parameters, PRUDENCE project was initiated. In this project, many state of the art high resolution regional climate models (RCM) with different boundary conditions (GCMs), varying resolutions and SRES emission scenarios are used. The climate scenarios used in this study are the outputs of regional climate models (i.e. RCAO, HIRHAM, RACMO, CLM) downscaled from the GCM HadAM3H (Hadley Centre) experiment run, based on SRES A2 emission scenario produced under the frame work of EU project PRUDENCE.

The climate scenarios are based on catchment average monthly precipitation and temperature output grid cells extracted in GIS-raster format from the PRUDENCE project homepage. The retrieved data sets are basically two time slices, one for recent conditions (1961-1990), and the other for future climate (2071–2100). The relative changes in both parameters, known as "climate scenarios" are presented as seasonal averages in Table I. All scenarios suggest winter temperature increase by 4.5°C and precipitation increase by 17% whereas, summer temperatures increase by 5.2 °C and the total amount of precipitation may decrease by 38%. The observed climate model projections are generally similar with the trends of the greater Alpine area projections except little variation in magnitude [10]. Earlier findings in [11, 12] also concluded that the Alps will be much wetter and warmer in winter, and drier and hotter in summer in the latter part of the 21st century. After model development (calibration and validation), the observed data base precipitation and temperature series (1961-1990) is perturbed with climate scenarios by means of the so called "delta change" approach. Similar methodology is also adopted in earlier studies [2, 13]. The delta-perturbed series are then utilized as input for the PREVAH model.

TABLE I. CATCHMENT RELATIVE CHANGES IN AVERAGE DAILY TEMPERATURE AND PRECIPITATION EXTRACTED FROM THE PRUDENCE PROJECT DATABASE

Season	Parameter	RCAO	RACMO	HIRHAM	CLM
Winter	Precipitation (%)	16.85	11.93	16.49	10.42
	Temperature (°C)	3.93	3.57	4.45	4.10
Spring	Precipitation (%)	5.27	9.37	2.95	12.92
	Temperature (°C)	3.47	3.37	3.46	3.55
Summer	Precipitation (%)	-37.84	-32.48	-21.59	-29.5
	Temperature (°C)	5.20	4.33	4.34	4.37
Autumn	Precipitation (%)	-13.89	-9.09	-19.9	-7.78
	Temperature (°C)	4.00	3.94	5.40	3.95

IV. Model development

The distributed model system PREVAH has been developed to represent hydrological characteristics of mountainous catchments. It has been successfully applied in a number of mountain catchments [2, 6, 7, 14-16] and is also applied to this study. The details about various data sets i.e. meteorological data, soil types, land use, land cover, elevation model, various modules and schemes used for model development for this specific catchment are given in [2]. For details about PREVAH model, see [17]. The first model was calibrated over the 1983-1988 period and the latter validated over the 30 year baseline period of 1961-1990. The results of calibration and validation periods are compared to the observed hydrographs both graphically and statistically, and are shown in Figures 2 and 3. The linear (Elin) and logarithmic (Elog)

Nash–Sutcliffe efficiencies are about 0.84 for calibration and above 0.80 for validation period and are shown in Table II.

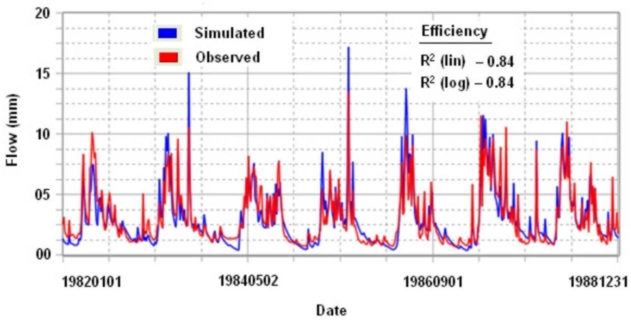

Fig. 2. Graphical comparison of observed and simulated daily hydrograph at the gauge station (St Johann i.T) of the Kitzbüheler Ache catchment for calibration period (1983-88).

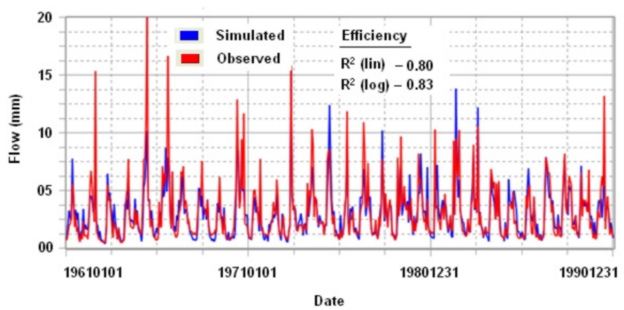

Fig. 3. Graphical comparison of observed and simulated daily hydrograph at the gauge station (St Johann i.T) of the Kitzbüheler Ache catchment for validation period (1961-90).

V. Results and Discussion

To analyze the effect of projected climate scenarios on base flow conditions, the base flow simulations for the period (2071-2100) are compared to present condition (1961-90) simulations. The mean monthly, present and future, base flow patterns along with percent deviation in volume are shown in Figure 4. Mean annual changes are illustrated in Figure 10. It is clearly highlighted that under the current situation, most of the base flow is produced in spring and early summer months. Snow melt is assumed to be the most important factor. However, the generation volume associates with the amount of winter snowfall, and corresponding degree and extent of snow melt season. The catchment average is approximately 753 to 794mm/year, approximately half the precipitation amount. In future context, this decreases by around 5-9%. At seasonal scale, winter volume is increased about 90% to 95%, whereas, in other seasons decreased about 9% to 15% for spring, 25% to 40% for summer, and 15% to 23% for autumn. In winter season, warm temperatures cause higher rain to snow ratio, thereby resulting in massive increase in baseflow volume.

However, at spatial scale, the distinct hydraulic properties of underlying soil result in variation of base flow volume across the watershed (Figure 5). Similar understanding is also reported in [18], that soil and other subsurface properties directly influence spatial variation in base flow volume. Snowfall trend is recognized to be the main cause behind variation in base flow volume. Snow cover maps given in Figure 6 endorse this assumption. Relative to present condition mean annual snow cover days (160 days), all models predicted reduced snow cover days: 74 days for CLM, 65 days for Hirham, 83 days for RACMO, and 76 days for RCAO model. An earlier onset of melt season due to increase in temperature results in shortened total snow cover days. These may have totally disappeared, but partially have been compensated by the increased winter precipitation trends. Another cause of variation in base flow volume can also be attributed to seasonal variation in precipitation trends and increased evaporative losses. The increase in evaporative losses is recorded in all seasons, with 10-15% relative loss at mean annual scale (Figure 6). The seasonal contributions to mean annual losses are changed from 6% to 10% for winter, 21% to 28% for spring, 50% to 52% for summer and 23% to 27% for autumn for all model scenarios. Similar trends of evaporative losses are also reported for Swiss catchments. The rising trend of temperature has significantly increased evaporative losses in winter and spring. However losses in remaining two seasons stayed at moderate side (Figure 7). The projected increased summer temperatures may have increased evaporative losses, but that is compensated due to reduced projected precipitation amount. In quantitative terms, summer losses are still at higher side.

TABLE II. MEAN MONTHLY ELIN AND ELOG VALUES FOR CALIBRATION AND VALIDATION PERIOD

Month	Calibration period (1983-88)		Validation period (1961-90)	
	Lin (E)	Log (E)	Lin (E)	Log (E)
Jan	0.89	0.91	0.92	0.90
Feb	0.96	0.92	0.89	0.86
Mar	0.81	0.77	0.77	0.76
Apr	0.84	0.83	0.79	0.78
May	0.88	0.93	0.82	0.87
Jun	0.85	0.87	0.78	0.81
Jul	0.76	0.79	0.83	0.80
Aug	0.82	0.77	0.76	0.79
Sep	0.79	0.78	0.77	0.75
Oct	0.84	0.79	0.79	0.85
Nov	0.90	0.87	0.80	0.89
Dec	0.80	0.91	0.83	0.87

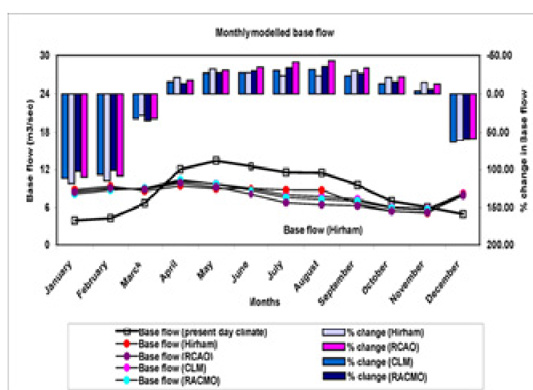

Fig. 4. The mean monthly baseflow values (2071-2100) with their corresponding present day (19961-1990) baseflow values along with monthly percentage change in volume under A2-emission scenario.

Projected climatic scenarios have also influenced seasonal patterns of environmental and total flow volume (Figure 8). A significant increase is observed in winter flow volume while decreasing trend is observed in the other three seasons. Relative to recent climate (1961-90), the average seasonal flow to mean annual flow is changed from 12% to 25% for winter, 34% to 27% for spring, 35% to 20% for summer, and 20% to 16% for autumn at the end of the 21st century. Peak flow pattern is switched from May to March-April along with reduced volume. An anticipated increase in spring flow volume due to projected increase in precipitation amount is compensated by early snow melting to winter months and greater evapotranspiration (Figure 7). A similar conclusion is also drawn in [5, 6, 11] for alpine catchment. The increased evapotranspiration along with decreased precipitation amount in summer and fall may also reduce flow volume in these seasons. Similarly, the projected environmental flows (Q95) follow the same identical patterns of projected total mean seasonal flow patterns. Low precipitation amount along with increasing evapotranspiration losses results in decreasing volume from April to September. Therefore, environmental flow trend may have serious consequences over quality and supply in summer months.

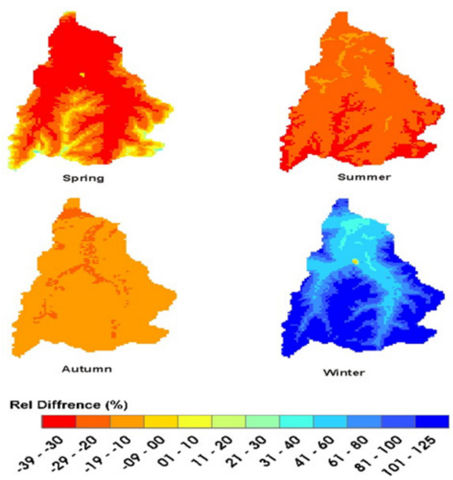

Fig. 5. The relative seasonal change in baseflow volume under A2-emission scenario.

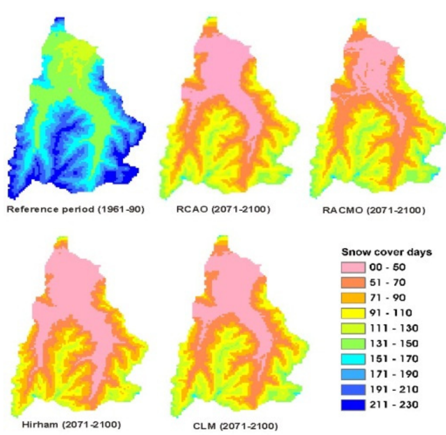

Fig. 6. The comparison of projected mean annual snow duration maps with their corresponding base period (19961-1990) snow duration map.

The changes in flow variables i.e. environmental flow and total mean flow may have altered water availability in various months. Figure 9 demonstrates this effect, where water availability is calculated by means of difference between total flow and environmental flow volumes. All model projections clearly show increasing patterns from December to March and decreasing patterns from May to August. However, marginal change is observed at mean annual scale (Figure 10). Projected total flows appear extremely critical from May to September, where they are just narrowed down to current environmental flow volumes.

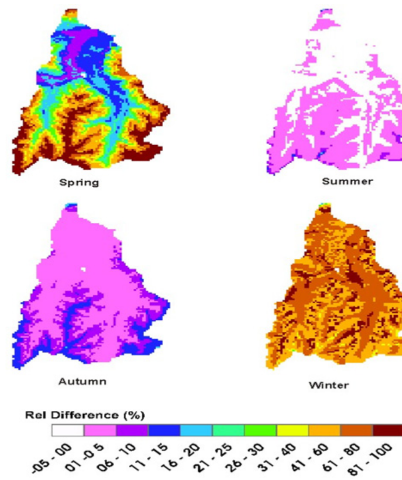

Fig. 7. The relative seasonal shift in actual under A2-emission scenario.

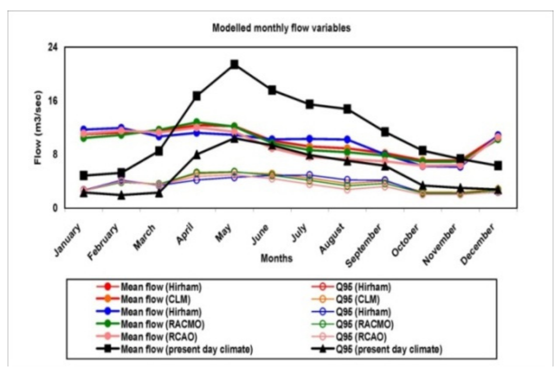

Fig. 8. The projected mean monthly environmental flow (Q95) and total stream flow regime under A2-emission scenario

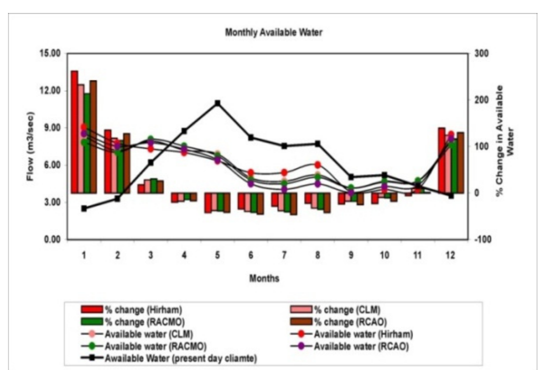

Fig. 9. The projected mean monthly available water (2071-2100) with their corresponding present day (19961-1990) values along with monthly percent of change in volume under A2-emission scenario.

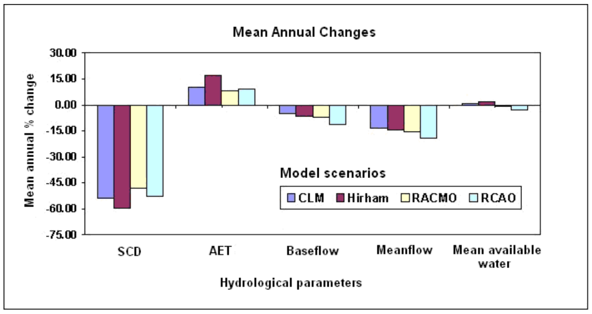

Fig. 10. The relative mean annual changes in snow cover duration (SCD), actual evapotranspiration (AET), baseflow (BF), total flow and total available water under A2-emission scenario.

VI. CONCLUSIONS

This study clearly demonstrates that catchment flow regime i.e. baseflow, environmental flow, and total flow is highly vulnerable to climatic variations. The projected increasing temperatures, seasonal shift in precipitation patterns, subsequent effect over high rain to snow ratio in winter, anticipated early onset of snowmelt season, and increasing evaporative losses are attributed to be the major driving factors behind a clear-cut shift in observed seasonality of flow variables. Relative to present condition scenario, the base flow volume in winter is increased about 90% to 95%, whereas is decreased, about 9% to 15% in spring, 25% to 40% in summer, and 15% to 23% in autumn. Further variation observed in base flow volume is non-uniform across the catchment at spatial scale. This could mainly be attributed to distinct hydro-geologic properties of underlying soil across the catchment. Moreover, projected model simulations also indicate the same identical pattern of changes in total mean flow, environmental flow as in base flow regime and subsequent effect over seasonal water availability patterns.

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