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The influence of constrained fossil fuel emissions scenarios on climate and water resource projections

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Abstract

Water resources planning requires long-term projections of the impact of climate change on freshwater resources. In addition to intrinsic uncertainty associated with the natural climate, projections of climate change are subject to the combined uncertainties associated with selection of emissions scenarios, GCM ensembles and downscaling techniques. In particular, unknown future greenhouse gas emissions contribute substantially to the overall uncertainty. We contend that a reduction in uncertainty is possible by refining emissions scenarios. We present a comprehensive review of the growing body of literature that challenges the assumptions underlying the high-growth emissions scenarios (widely used in climate change impact studies), and instead points to a peak and decline in fossil fuel production occurring in the 21st century. We find that the IPCC's new RCP 4.5 scenario (low-medium emissions), as well as the B1 and A1T (low emissions) marker scenarios from the IPCC's Special Report on Emissions Scenarios are broadly consistent with the majority of recent fossil fuel production forecasts, whereas the medium to high emissions scenarios generally depend upon unrealistic assumptions of future fossil fuel production. We use a simple case study of projected climate change in 2070 for the Scott Creek catchment in South Australia to demonstrate that even with the current suite of climate models, by limiting projections to the B1 scenario, both the median change and the spread of model results are reduced relative to equivalent projections under an unrealistic high emissions scenario (A1FI).

1 Introduction

It is widely anticipated that anthropogenic climate change will have significant impacts on freshwater resources worldwide (Kundzewicz et al., 2007). Large-scale water resources infrastructure such as dams, pipelines and desalination plants are typically designed for service lives of 50 years or more. With such long planning horizons, it is particularly important within the water industry to understand the uncertainty surrounding long-term projected impacts of climate change and to find ways to minimize this uncertainty.

Sivakumar and Sharma (2009) summarized the scientific challenges that we face in the sustainable management of our future water resources. These challenges include identification of the actual causes of climate change, development of General Circulation Models (GCMs) that can adequately incorporate these causes to generate dependable future climate projections at larger scales, formulation of appropriate techniques to "transform" (i.e. downscale) the GCM outputs to regional and local conditions for hydrological analysis and projections, and reliable estimation of the associated uncertainties in all these steps.

There is currently a somewhat controversial landscape with respect to the perceived relevance or irrelevance of GCMs to hydrological studies. The debate is largely centered around the question of whether GCMs are capable of reproducing realistic climate characteristics (Koutsoyiannis et al., 2009b; Kundzewicz et al., 2009). Anagnostopoulos et al. (2010) compared the outputs of several GCMs with observed temperature and precipitation data, concluding that, even on large spatial and temporal scales, the models do a poor job of representing the observed climate. They concluded that a deterministic approach to climate modeling was insufficient, and that future projections must consider the intrinsic or "structural" uncertainty of hydrology (and climate in general), which may be more appropriately represented by a stochastic approach. The point of structural uncertainty was also made by Koutsoyiannis (2010), who demonstrated that even a simple deterministic "toy" climate model without external forcings can produce chaotic and uncertain results, fluctuations, and trends similar to those observed in the real world climate. In related articles, Wilby (2010) and Kundzewicz and Stakhiv (2010) both recognised the original intent of GCMs, namely to assess the global climatological implications of different emissions pathways, in contrast to the more recent tendency to use such models to drive regional or local hydrological impact assessments. Wilby (2010) concluded that "characterising" uncertainty in climate

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projections may be more achievable than "reducing" uncertainty. While recognising these significant ongoing issues relating to overall climate uncertainty and model appropriateness, in the following discussion we will show that: (a) the current wide range of "plausible" greenhouse gas emissions scenarios presents a significant source of uncertainty in modeled future climate; and (b) there is significant scope to reduce this range, and thereby reduce some of the uncertainty.

The main stages in developing a model of the hydrological impacts from climate change are shown in Fig. 1. When attempting to make a future projection, as opposed to a hypothetical scenario or numerical experiment, the uncertainty begins with the need to arbitrarily choose a greenhouse gas emissions scenario, and this initial uncertainty is then compounded by further modelling variability all the way to the final catchment-scale projection. The uncertainty introduced at each step comes from the need to choose from a (sometimes diverse) range of models, plus variability in the observational data used to parameterise each model.

Given the compounding nature of these uncertainties in modeled climate projections, it is important to understand where (or when) particular factors are dominant. Hawkins and Sutton (2009) gave a useful assessment of the three main sources of uncertainty in current projections for global temperature change and related this to the timescale of the projection. The sources of uncertainty they considered were:

1. internal variability (natural climatic variability and short-term changes that can cause temporary departures from longer-term trends);
2. model uncertainty (differences in numerical schemes, modelling assumptions, coupling processes, parameterization, etc.); and
3. scenario uncertainty (differences in projected greenhouse gas (GHG) emissions and the resultant climate forcing).

They showed that in the short to medium term (several decades), model uncertainty dominates the overall uncertainty in temperature projections. However, according to

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Hawkins and Sutton (2009), the relative influence of scenario uncertainty grows rapidly over time and by 2100, scenario uncertainty dominates overall uncertainty (almost four times more than the model uncertainty). For long-term projections of global temperature change, internal variability was shown to be negligible.

A similar analysis of uncertainty in future precipitation changes was undertaken by Hawkins and Sutton (2010), who found that, unlike temperature, a combination of modeling uncertainty and internal variability heavily dominates projected global and regional changes in precipitation up to 2100. This supports earlier research by Covey et al. (2003) and Arnell (2003) who found that the variability in long-term hydrological predictions were dominated by modeling differences rather than by emissions trajectories. In short, the current GCMs are unable to produce a consistent projection of long-term precipitation changes either regionally or globally. This is in part due to the fact that precipitation, unlike temperature, is a secondary variable or output from GCMs. This is unfortunate because while it might be a secondary output from a GCM, precipitation is a primary input to hydrological models. Despite this significant issue, emissions scenario uncertainty remains an important source of uncertainty in hydrological projections, for three reasons:

1. temperature change (for which models are in broad agreement over the long-term, and for which emissions scenario choice is important) is hydrologically significant, both directly due to its role in evaporation (Morton, 1983), and indirectly via its interaction with the global carbon cycle (Friedlingstein et al., 2006);

2. plant growth is highly dependent on temperature and atmospheric CO_2 (both of which substantially depend on the emissions scenario), and modeled vegetation processes have been shown to contribute significantly to the hydrological cycle, especially runoff (Betts et al., 2007); and

3. future advances in modeling techniques and improved understanding of the relative performance of individual models (Knutti, 2010; Smith and Chandler, 2010)

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are expected to reduce model uncertainty in precipitation projections, thereby placing a greater emphasis on emissions scenarios.

There is an emerging, but steadily growing body of research (Brecha, 2008; Höök et al., 2010; Nel and Cooper, 2009; Murray, 2009; Ward and Nel, 2010; Rutledge, 2011) that constrains future fossil fuel projections to the lower end of the range currently being considered in climate change studies. In this paper it is argued that these limits to future fossil fuel consumption should be considered in the selection of emissions scenarios. The primary objective of the current paper is to explore the likely implications of limits to fossil fuel production (and the subsequent constraint on CO_2 emissions) on predictive uncertainty, within the broader context of the importance of emissions scenarios for freshwater resource projections. The recent advances in fossil fuel research may assist in reducing uncertainty for long-term projections of climate change impacts, which would be significant for water resource planners.

A brief history of climate scenarios is presented, as well as a review of the growing body of literature on fossil fuel constraints that challenge the GHG emissions assumptions underlying the majority of emissions scenarios currently in use in impact studies. A case study is then used to demonstrate that even with the current suite of models, a substantial reduction in overall prediction uncertainty may be achieved by implementing realistic fossil fuel forecasts.

2 Climate scenarios used in water resource projections

Climate scenarios have been evolving since the earliest numerical modeling in the 1960s and Moss et al. (2010) provide a useful timeline of their development. Climate scenarios can be broadly grouped into two categories. The first category (the right-hand side of Fig. 1) involves a series of "plausible" projections of future climate based on GHG emissions, which are usually accompanied by projections of global and regional populations and economic growth (among other variables). These types

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of projections have been prominent in many recent impact studies and have included the IS92 series (Leggett et al., 1992), later replaced by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios, or SRES (Nakicenovic and Swart, 2000). The SRES scenarios contained 40 "storylines" describing global and regional population growth, economic growth and technology change, and gave the resulting GHG emissions in each case. The 40 scenarios are divided into four "families" (A1, A2, B1, B2) describing core assumptions of future regional and global population growth, economic development, energy use and other factors. To simplify comparison studies, each family is given a representative "marker" scenario. In addition to the four marker scenarios, two extra marker scenarios from the A1 family are included by Nakicenovic and Swart (2000). These are the A1G MINICAM (more commonly known as A1FI), which denotes a fossil fuel intensive trajectory, and A1T, which denotes a predominantly non-fossil fuel trajectory. The cumulative emissions under each marker scenario are summarized in Table 1. The name of each marker scenario (AIM, MESSAGE, etc.) refers to the modeling group responsible for converting the qualitative storyline into a quantitative greenhouse gas emissions pathway. Nakicenovic and Swart (2000) explicitly state that all scenarios have equal likelihood, and Manning et al. (2010) observe that cumulative global GHG emissions (and resultant atmospheric CO_2 concentrations) from 1990–2008 were approximately in the middle of the range of the six marker scenarios.

The second category of future climate projections involves purely "academic" scenarios (the left-hand side of Fig. 1). These do not claim to project plausible futures, but instead investigate the impact of some hypothetical perturbed climate relative to a control experiment. For example, this could compare the difference between two simulated climates where one undergoes a 1% p.a. steady increase in atmospheric CO_2 and the other has static CO_2 concentrations (Covey et al., 2003), or it could compare the difference in simulated climates between a pre-industrial situation and a "doubled-CO_2" scenario (Allen et al., 2003).

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Given the dominance of model uncertainty in long-term precipitation uncertainty (Hawkins and Sutton, 2010) in most studies of projected climate change impacts on water resources, the influence of the emissions scenario (or scenario uncertainty) is not the focus of the investigation. Rather, these studies tend to focus on novel climatic or hydrological modeling techniques and the associated assumptions and uncertainties. For instance, Douville et al. (2002) presented the results of a global rainfall and runoff model considering two scenarios: constant 1950s GHG emissions (control case) versus the SRES B2 marker scenario with CO_2 rising to 620 ppm by the end of the 21st century. With only one future emissions trajectory being tested, such a study could not quantify the influence of different possible emissions pathways. Similarly, Döll (2002) presented the results of a model for global irrigation demand, based on the outputs of two GCMs and one emissions scenario (IS92a). Booij (2005) modelled the Meuse River basin discharge under current and changed climates, considering a "current" climate (1970–1999) and an academic scenario of a hypothetical doubled-CO_2 climate. Betts et al. (2007) investigated global runoff changes under a simulated pre-industrial climate versus a doubled-CO_2 climate. Downing et al. (2003) considered multiple emissions scenarios covering a wider range of possible long-term futures. However the focus of the project was limited to the 2020s, which proved too short a timeframe for the various emissions scenarios to significantly diverge.

CSIRO (2007) analysed the results of 23 GCMs extending to the 2070s and for each model evaluated changes in annual and seasonal temperature, precipitation, wind speed, solar radiation and potential evaporation across the Australian continent, relative to a baseline period of 1980–1999. They considered three marker scenarios from SRES – low (B1), medium (A1) and high (A1FI) – and presented the results visually as 10th, 50th and 90th percentiles to demonstrate the spread of model results across each scenario. The graphical results are available online (http://www.climatechangeinaustralia.com.au/futureclimate.php, accessed on 11 January 2011). For changes to rainfall in the long-term (2070s), the most obvious source of uncertainty is from model differences. However, both the median change and the spread of model results depend (albeit slightly) on the choice of emissions scenario. As expected, the results of CSIRO (2007) for long-term change in temperature and potential evaporation show a more obvious dependence on emissions scenario than was observed for rainfall, with a substantial increase in both the median and the model spread under high emissions, relative to the low emissions scenario. We revisit the results of CSIRO (2007) in our case study below.

A recent advance in the development of emissions scenarios was reported by Moss et al. (2010), with a new suite of scenarios to replace SRES in the IPCC's forthcoming Fifth Assessment Report (AR5), and in future climate change impact studies. The new range consists of four projections of radiative climate forcing, which are independent of socio-economic or GHG emissions projections (see Fig. 1). For those interested in making climate change projections based on plausible future GHG emissions trajectories, Moss et al. (2010) have proposed a "representative concentration pathway" (RCP) for each scenario, taking specific emissions pathways that could plausibly lead to each of the four radiative forcing pathways, although they are careful to explain that there are multiple possible emissions scenarios that could lead to the same ultimate radiative forcing outcome. The four RCP scenarios are summarized in Table 2 in terms of cumulative emissions over the 21st century, long-term concentrations of atmospheric CO_2 (equivalent) and the resultant radiative forcing.

One significant issue with all emissions scenarios is that the global carbon cycle and associated climate feedbacks remain a major source of uncertainty in the relationship between GHG emissions pathways and the ultimate radiative forcing (Moss et al., 2010; Friedlingstein et al., 2006; Jones et al., 2006). For instance, GCMs which can couple climate change to the carbon cycle are yet to converge on a consistent result for CO_2 feedback, which presently varies from 20 ppm to 200 ppm over a 100 year simulation for a single emissions scenario, depending on the model (Friedlingstein et al., 2006). In this paper, we follow the convention that low emissions pathways correspond broadly to low radiative forcing pathways, and high emissions pathways correspond broadly to high radiative forcing pathways.

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For each emissions scenario, it must be assumed either implicitly or explicitly that there is sufficient fossil fuel remaining to be produced and burnt, and that this fuel can be extracted at a growing rate that produces the projected rise in atmospheric CO_2 (see Nakicenovic and Swart, 2000). The factors controlling most of the hypothetical emissions pathways are economic, social and political (e.g. the future rate of population growth, rising affluence in developing countries and the potential national or global adoption of GHG emissions reduction policies), while the concept of physical constraints to actual future fossil fuel production has been dismissed (Höök et al., 2010).

3 Fossil fuel resources as a constraint to emissions scenarios

The limits to the Earth's fossil fuel resources have been widely discussed for more than half a century. These discussions have been influenced by Hubbert (1949, 1956), as well as the Club of Rome (Meadows et al., 1972), and a series of lectures and articles by Bartlett (1978, 1981, 1994, 2000), among others (e.g. Laherrere, 2001; Bentley, 2002). As in climate modeling, improvements to computer technology and modeling techniques have led to increasingly sophisticated estimates for fossil fuel reserves and predictions for future production rates, and these predictions are gradually converging. Recent analyses have included predictions of both future oil production (Mohr and Evans, 2008; Aleklett et al., 2010) and coal production (e.g. Mohr and Evans, 2009; Höök and Aleklett, 2009; Lloyd and Subbarao, 2009; Lin and Liu, 2010; Patzek and Croft, 2010). Mohr (2010) presents a combined estimate for world oil, coal and natural gas production. The consensus emerging in the literature is that fossil fuel production is nearing a peak and will decline sometime in the 21st century, as the larger, mature fields reach the end of their productive life and are replaced with either smaller resources, or resources that are slower to extract.

Despite the long-term discussion of fossil fuel resource limits, many projections of future anthropogenic climate change have assumed that continuous growth in GHG

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emissions will be possible for several centuries (i.e. long enough to trigger significant climate change). Höök et al. (2010) reviewed the development of the IPCC's emissions scenarios, mostly referring to Nakicenovic and Swart (2000), and contrasted these scenarios against the growing body of literature regarding fossil fuel depletion. They criticized the "unnecessarily optimistic" assumptions of continual growth in fossil fuel production by the IPCC.

Only recent research has reconciled fossil fuel limits and emissions scenarios. Laherrere (2001) was among the first to explicitly challenge the IPCC's assumption that continual growth in fossil fuel production would be possible, claiming instead that global oil and gas production would barely keep up with the lowest of the SRES scenarios through the 21st century. Doose (2004) discussed fossil fuel limits, GHG emissions and climate change, and based on a simplistic carbon sink model and a basic fossil fuel production model, concluded that future atmospheric CO_2 concentrations may not rise any higher than 650 ppm. There have been similar studies by Kharecha and Hansen (2008) who investigated a range of hypothetical future fossil fuel scenarios with declining oil production with a simple carbon sink model, and found that CO_2 concentrations could be limited to around 450 ppm, but this would depend on not exploiting excess coal or unconventional fossil fuels. Brecha (2008) presented a similar analysis, concluding that the maximum CO_2 concentration under a "high emissions" scenario, but constrained by resource limits, may be approximately 560 ppm, peaking around the year 2075.

Nel and Cooper (2009) presented several possible fossil fuel production trajectories and challenged the strength of climate-carbon cycle feedbacks as assumed in the BERN carbon cycle model (Siegenthaler and Joos, 1992). Nel and Cooper (2009) showed that under their high fossil fuel reserves scenario, using a parameterized carbon feedback model calibrated to empirical evidence, atmospheric CO_2 concentrations would peak at 440–480 ppm around the year 2070, falling to 340–360 ppm by 2200. They also showed that under the BERN carbon cycle model (a process-based model without corrections for missing sinks), the same fossil fuel scenario would result in

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peak CO_2 concentrations of 540 ppm around the year 2100, remaining above 500 ppm through to 2200. The issue of positive versus negative carbon cycle feedback assumptions under low emissions trajectories was identified earlier by Kharecha and Hansen (2008), who made the point that under low emissions scenarios, a negative feedback (where carbon sinks remain effective) may result in a climate forcing that is much less than that under scenarios with continually rising emissions and positive carbon cycle feedbacks. Tans (2009) used oceanic and atmospheric observations of carbon to constrain an empirical carbon sink model, and concluded that the carbon cycle has become more effective over recent years in removing anthropogenic CO_2 from the atmosphere. Using a simple logistic model of future fossil fuel production to 2500, Tans (2009) predicted atmospheric CO_2 concentrations would peak at 500 ppm in the year 2069 (for a conventional resources scenario) and 600 ppm in the year 2090 (for a conventional + unconventional oil resources scenario). Tans (2009) extended his results to consider possible future radiative forcings, which were predicted to peak in the same years as atmospheric CO_2 concentration, at 3 $W\,m^{-2}$ (conventional) and 4 $W\,m^{-2}$ (conventional + unconventional), broadly consistent with the RCP 2.6 and RCP 4.5 scenarios from Moss et al. (2010) (see Table 2).

Rutledge (2011) provided a detailed history of world coal production and presented a method for predicting ultimate production based on historical trends. He observed that in mature coal-producing regions, early coal reserve estimates have consistently been much higher than the ultimately recovered amount, yet downward revisions to reserve estimates typically occur quite late in the production history. Rutledge (2011) also discussed the important differences between "reserves" (coal that can be produced economically with current technology) versus "resources" (coal that could potentially be produced in the future), and the tendency for large amounts of coal to move between these classifications due to periodic changes in estimation techniques or policies. Importantly, Rutledge (2011) pointed out that there is a further category (called "additional recoverable reserves") that has proven very unreliable in historical surveys. However the SRES predictions for high future coal production (Nakicenovic and Swart, 2000)

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are dependent on a single, apparently anomalous estimate of additional recoverable reserves by the World Energy Council (WEC, 1998). The WEC subsequently downwardly revised its estimates, and by 2007 was stating global coal reserves totaling less than one quarter of their 1998 estimated value (WEC, 2007). While Rutledge (2011) predicted only ultimate coal production, a prediction for future coal production rates was presented by Patzek and Croft (2010) via a multi-Hubbert cycle analysis for different producing regions, concluding that global coal production (and associated GHG emissions) would peak as early as 2011, and decline to half of the peak production rate by 2047.

With the mounting arguments for fossil fuel limits, there is now an opportunity to refine the emissions scenarios adopted in climate change impact studies. Figure 2 shows a comparison between fossil fuel GHG emissions (solid lines) from the studies reviewed above, versus the new RCP scenarios (dashed lines) from Moss et al. (2010). For brevity, we have included only those projections where a CO_2 emissions trajectory was included in the published study; many other studies of future fossil fuel production focus on energy but do not convert produced fuel into emissions. The 40 SRES scenarios are included (faint grey lines) in the background of the plot, for reference. It should be noted that current fossil fuel emissions are approximately 8.5 GtC yr^{-1} (Myhre et al., 2009; Manning et al., 2010), which is roughly in the middle of the range of projections.

From Fig. 2, it can be seen that most of the SRES scenarios are significantly overpredicting emissions from around 2030 onwards with respect to the more recent studies of future fossil fuel production. The low-medium RCP 4.5 scenario offers the best visual match to the recent studies. The low scenario RCP 2.6 appears to be slightly too low, while the high scenario RCP 8.5 (similar to the upper SRES scenarios) corresponds to unrealistic fossil fuel production. The RCP 6.0 scenario (medium-high) is also unrealistic with respect to most scenarios, the exceptions being Kharecha and Hansen's (2008) high business-as-usual (BAU) scenario and the unconventional fossil fuel scenario from Tans (2009). Kharecha and Hansen's (2008) high BAU scenario is hypothetical in nature, assuming a steady 2% p.a. growth in global production of each

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fossil fuel (coal, oil and gas) until half of the global reserve remains, at which point production switches to a decline of 2% p.a. This does not represent a sophisticated attempt to predict actual future fossil fuel production. It should be noted that Brecha's (2008) scenarios are, like Kharecha and Hansen's high BAU scenario, similarly hypothetical in nature. The high scenario of Tans (2009) was simplistic, and involved the optimistic assumption of a seamless adoption of unconventional fossil fuels (shale oil, bitumen and heavy oil) to sustain a 2 to 3% annual growth in total fossil fuel production over the next few decades. Mohr and Evans (2010) provided a more sophisticated modeling approach for unconventional oil, and concluded in their "best guess" scenario that total oil production (conventional + unconventional) would begin declining within 5 years.

Because the RCP scenarios (Moss et al., 2010) have yet to be widely implemented in climate change impact studies, it is relevant to also compare the performance of SRES scenarios (on which the majority of studies have been based) against fossil fuel production studies. Figure 3 shows the same fossil fuel studies presented in Fig. 2, but this time we compare them against the six SRES marker scenarios (Nakicenovic and Swart, 2000). The closest agreement is found with the B1 and A1T marker scenarios. The A1G MINICAM (A1FI) and A2 marker scenarios do not correspond to realistic fossil fuel production trajectories. The A1 and B2 scenarios are somewhat similar to the RCP 6.0 scenario, and are higher than the majority of fossil fuel projections.

It is important to note that low emissions do not guarantee a future free of significant climate change. Allen et al. (2009) and Meinhausen et al. (2009) both present results of a simplified coupled climate-carbon cycle model that shows how even low emissions pathways may potentially lead to a global mean surface temperature (GMST) increase in excess of 2 °C, with results depending on the assumptions of the models. There are multiple (compounding) layers of model uncertainty associated with coupled climate-carbon cycle models, and until recently there has been a lack of observational data to constrain model parameters (Jones et al., 2006). However, recent observational evidence has been presented suggesting that climate-carbon cycle feedbacks may be at the lower end of the range previously being considered (Mahecha et al., 2010; Frank et al., 2010). If, in the future, more sophisticated coupled climate-carbon cycle models (constrained by more reliable observational data) converge on a particular level of feedback (low or high), then current climate change forecasts may need to be revised. The positive aspect of this (even if feedbacks turn out to be high) would be that overall model uncertainty would be reduced. Irrespective of whether ultimately agreed feedbacks are high or low, it will be even more important to consider the most realistic emissions scenarios available.

4 Case study – Scott Creek Catchment, South Australia

A case study is presented here to demonstrate the influence of emissions scenario choice on projected climate change impacts, using a simple hydrological model and scenario framework. This case study is intentionally brief and full details of the study area, methodology and hydrological modelling are provided in Haith et al. (1992) and Banks et al. (2009).

4.1 Site description

The research catchment, Scott Creek, is a 28.5 km^2 upland catchment in the Mt Lofty Ranges, South Australia (location: 35°03′–35°07′ S, 138°38′–138°44′ E). The creek is approximately 10 km long with the lower 8.5 km flowing perennially. The catchment is an active hydrogeology research site (Harrington, 2004; James-Smith and Harrington, 2002; Kwantes, 2006; Werner et al., 2008; Banks et al., 2009). Interest in Scott Creek is further stimulated by the fact that the creek flows into the Onkaparinga River, upstream of a major water supply dam for the city of Adelaide. In addition, the stream has a substantial historical data record including 38 years of daily flow recording, and 34 years of salinity observations.

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4.2 Model description and calibration

The model developed in this study is based on the Generalized Watershed Loading Function (GWLF) from Haith et al. (1992). GWLF uses linear assumptions and two sub-surface compartments. Previous application of this model has demonstrated its success at modelling stream flow and non-point source pollutant loadings, such as nutrients and sediment loads (Lee et al., 2000, 2001; Schneiderman et al., 2002). This model uses the parsimonious Curve Number (CN) approach to calculate surface runoff. The CN approach accounts for catchment soil type, land-use and antecedent moisture condition to predict the runoff fraction of a rainfall event (Mishra and Singh, 2003). The CN approach does not distinguish between infiltration and saturation excess runoff, shallow unsaturated sub-surface flow and direct channel precipitation (Garen and Moore, 2005); nor does it account for the baseflow portion of the hydrograph. Saturation excess runoff occurs when the soil can no longer store more water, in which case any rainfall immediately runs off. Infiltration excess runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil, and the rainfall that cannot be absorbed is converted to runoff. GWLF non-specifically routes deeper sub-surface flow through shallow saturated zones to the stream. In this study, GWLF is combined with a salinity mixing model. The model is calibrated to an objective function that integrates stream salinity and stream flow hydrograph simulation error. Figure 4 compares observed and simulated streamflows for the calibrated model.

4.3 Climate change scenarios

CSIRO (2007) reviewed 23 GCMs and summarised the seasonal changes to key climatic variables in Australia (including rainfall, wind speed, temperature and potential evaporation) by 2030, 2050 and 2070. They expressed these changes as percentile values (10th, 50th and 90th) relating to the number of models exceeding each value. Hence they present a “best guess” (i.e. the median of the model results) as well as a measure of the spread across the model results.

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For this case study, we have adopted a simple approach to generating future climate change scenarios. Rather than compounding the modelling uncertainty through additional steps (for instance, downscaling of GCM results and/or use of a stochastic weather generator), we have simply taken the daily weather observation data for the site and perturbed each value according to the regional seasonal projected changes from CSIRO (2007) for the low emissions marker scenario (B1) and high emissions marker scenario (A1FI). All perturbed values are for a 20-year period centred around 2070, relative to the baseline period of 1980–1999. Perturbations for rainfall and potential evaporation are shown in Table 3, where the GCM spread is shown by percentile rankings as in CSIRO (2007). For each emissions scenario, we use the 10th, 50th and 90th percentile changes to generate separate perturbed climate sequences for input to GWLF, so that the model covers the spread of GCM results and in turn produces upper, median and lower projections of runoff, streamflow and TDS. The process is illustrated schematically in Fig. 5.

We recognise that there are limits to such an approach but for the purpose of demonstrating the influence of emissions scenario on hydrological model outputs, this method is thought to produce a sufficiently plausible set of perturbed climate sequences to allow a meaningful comparison.

4.4 Results

A one year time-slice of the streamflow hydrograph is presented for the year 1999, for low emissions (Fig. 6) and high emissions (Fig. 7) to qualitatively illustrate the influence of the emissions scenario on GWLF model results. In the low emissions scenario, it can be seen that the predicted hydrograph for the median case represents only a modest change relative to the baseline. Model spread is large relative to the predicted change, with the upper bound indicating an increase in streamflow and the lower bound indicating a decrease of a similar magnitude. In the high emissions scenario, the upper case is almost identical to that for the low emissions scenario. However, both the

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median and lower cases are substantially lower, indicating a much larger spread of model results.

Table 4 shows the annual average value for a number of key model outputs over the 1980–1999 baseline period, as well as each perturbed climate change scenario. To compare the influence of the emissions scenario quantitatively, for each emissions scenario we define model spread S as the difference between extreme model predictions (where the input climate sequence was perturbed by the 10th and 90th percentile GCM projections) divided by the median:

$$S = \frac{|P_{10} - P_{90}|}{P_{50}} \tag{1}$$

where P_n is the predicted value of a variable of interest and the subscript n represents the percentile ranking of the scenario. We also define a proportional change C_{50} as the difference between the median prediction and the baseline value, divided by the baseline value:

$$C_{50} = \frac{P_{50} - P_{\text{baseline}}}{P_{\text{baseline}}} \tag{2}$$

S and C_{50} are evaluated for each model output (from Table 4), and the results are shown in Table 5.

By quantifying both the proportional change (C_{50}) and the model spread (S), we see that both parameters are substantially influenced by the emissions scenario. Under a high emissions scenario, C_{50} is 60–100% greater than under a low emissions scenario. Although S is large in both the low and high emissions scenarios, it is important to observe that in all parameters except evaporation, S is approximately 100% greater in the high emissions case than in the low emissions scenario (and in the case of evaporation, S is 70% greater under high emissions than low emissions). This suggests that if the A1FI scenario was eliminated on the basis of fossil fuel resource limits, and instead only the B1 scenario was considered as suggested by published studies on fossil fuel

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constraints, a significant reduction would result in (a) the magnitude of the projected change and (b) the uncertainty surrounding that projection.

5 Sustainability issues beyond climate change

In some studies, it has been the non-climatic aspects of the future scenario, such as the assumptions of regional population growth, that dominate the result, rather than the climate change itself. For instance, Arnell (2004) investigated water scarcity under SRES scenarios and noted that regional water scarcity was intimately linked to population, and that population growth projections varied significantly between scenarios. Vörösmarty et al. (2000) had previously reported similar results over a shorter time-frame (to 2025), where global population growth dominated the water scarcity problem.

Koutsoyiannis et al. (2009a) described the chaos and uncertainty (internal variability) inherent in rainfall patterns and compared this to the rather more certain projections of population growth and energy shortages. They suggested that planners should at least give increased consideration to environmental, social and economic changes other than climate change. This supports a similar conclusion of Nel and Cooper (2009), who proposed that energy shortages will present a much greater problem than climate change. If the conventional projections of high fossil fuel growth prove impossible, then there are profound implications for communities. Apart from the significance this has for climate change uncertainty, energy is crucial to the global economy and human wellbeing, and lower-than-projected energy availability suggests real limits to the global economy. Nel and van Zyl (2010) presented a new economic model that accounted for energy resource constraints, projecting a reduction in global GDP in the second half of the 21st century. Hamilton (2009) contended that the 2008 Global Financial Crisis was itself triggered by high oil prices. These factors, coupled with the relative certainty of ongoing global population growth, point to severe problems outside of climate change.

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6 Conclusions and recommendations

Emissions scenarios are a significant factor for long-term projections of water resources and reducing the spread of emissions scenarios would help to reduce overall uncertainty in climate projections. A body of literature is emerging that points to a peak and decline in global fossil fuel production occurring sometime in the 21st century and this provides an opportunity to refine emissions forecasts. It appears that the current upper emissions scenarios can probably be rejected, and the medium scenarios may also be unrealistic, leaving the low and low-medium scenarios as the most likely future for planning purposes. Specifically, recently published fossil fuel trajectories appear to be consistent with either the B1 or A1T marker scenarios from SRES, or the low-medium RCP 4.5 scenario from the new RCP series soon to be adopted in the IPCC's Fifth Assessment Report (AR5). A simple case study has shown that limiting projections to the low emissions (B1) scenario can result in a reduction in uncertainty for changes to hydrological variables such as rainfall, evaporation, runoff and streamflow.

There is still considerable uncertainty as to whether a low emissions trajectory (due to either climate change policy or due to reaching natural fossil fuel limits) could still be sufficient to trigger significant climate change. Improved dialogue is needed between climate modelers, fossil fuel forecasters and policy-makers.

Physical climate variables, such as emissions, temperature and rainfall, and socio-economic variables, such as population, GDP and human wellbeing, all need to be addressed in light of projected limits to fossil fuel energy production. In addition, these should all be incorporated into revised socio-economic scenarios. Existing climate change projections should be revisited on a case-by-case basis, to ascertain whether particular impact or adaptation studies need to be re-run with lower emissions scenarios.

For climatic and hydrological modelers with an interest in generating realistic scenarios for adaptation purposes, there may be merit in a shift in focus away from the debate around increasingly uncertain impacts from the highest emissions trajectories, and more towards the development of improved regional models, to understand in more detail the most likely impacts from a lower degree of global warming. For water resources planning, it would be prudent to consider climate change impacts as a potential source, but not the only source, of vulnerability over the next 100 years. For example, the lack of energy for pumping and treating water, as well as for building and maintaining infrastructure, may be a significant source of future vulnerability for freshwater resource managers, irrespective of climate change impacts.

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Table 1. Cumulative projected emissions under six SRES marker scenarios (after Nakicenovic and Swart, 2000).

Marker Scenario	Cumulative emissions (GtC)	
	1990–2050	1990–2100
A1 AIM	730.6	1492.1
A2 ASF	728.6	1855.3
A1G MINICAM (A1FI)	820.9	2182.3
B2 MESSAGE	554.5	1156.7
A1T MESSAGE	623.1	1061.3
B1 IMAGE	599	975.9

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Table 2. RCP scenarios (from Moss et al., 2010).

Scenario	Radiative forcing	Atmospheric concentration (ppm)	Approx. cumulative emissions (GtC) 2000–2100
RCP 2.6	~3 $W m^{-2}$ before 2100, then declines	Peak at ~490 CO_2 equiv. before 2100 then declines	370
RCP 4.5	~4.5 $W m^{-2}$ at stabilization after 2100	~650 CO_2 equiv. at stabilization after 2100	830
RCP 6.0	~6 $W m^{-2}$ at stabilization after 2100	~850 CO_2 equiv. at stabilization after 2100	1260
RCP 8.5	>8.5 $W m^{-2}$ in 2100	>1370 CO_2 equiv. in 2100	1960

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Table 3. Changes to rainfall and Potential Evaporation for the Fleurieu Peninsula region (from CSIRO, 2007).

	Rainfall: % change – 2070 relative to 1980–1999							
	low emissions				high emissions			
Percentile	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
10	–30	–15	–15	–30	–30	–30	–30	–50
50	–3.5	–3.5	–7.5	–15	–7.5	–7.5	–15	–30
90	15	15	0	0	30	15	3.5	3.5
	Potential Evaporation: % change – 2070 relative to 1980–1999							
	low emissions				high emissions			
Percentile	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
10	0	3	3	0	0	6	6	0
50	3	6	10	3	6	10	14	6
90	6	10	18	6	14	18	18	10

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Table 4. Model outputs under baseline and climate change scenarios.

	Mass balances – average annual (1980–1999)							
			Low emissions			High emissions		
Units	Variable	baseline	10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
mm	Rainfall	801	642	737	839	523	672	869
mm	Evaporation	504	450	502	546	415	484	565
mm	Runoff	7.82	3.09	5.07	8.76	0.93	3.23	9.83
mm	Streamflow	130	86	104	129	52	85	134
tons/ha	TDS	0.30	0.23	0.26	0.29	0.18	0.23	0.30

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Table 5. Model spread and proportional change.

	Model Spread (S)		Proportional Change (C_{50})	
	low emissions	high emissions	low emissions	high emissions
Rain	27%	51%	−8%	−16%
Evaporation	19%	31%	−1%	−4%
Runoff	112%	275%	−35%	−59%
Streamflow	41%	97%	−20%	−35%
TDS	25%	54%	−13%	−23%

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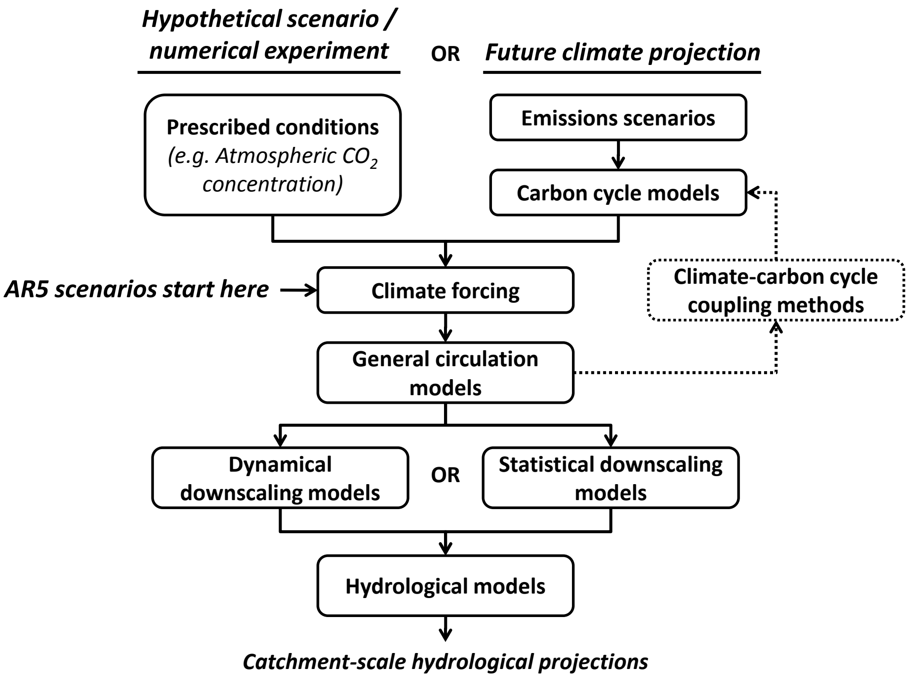

Fig. 1. Simplified chart of the main processes involved in modeling hydrological impacts from climate change. Note: dashed lines around climate-carbon cycle coupling methods indicate that not all models are coupled.

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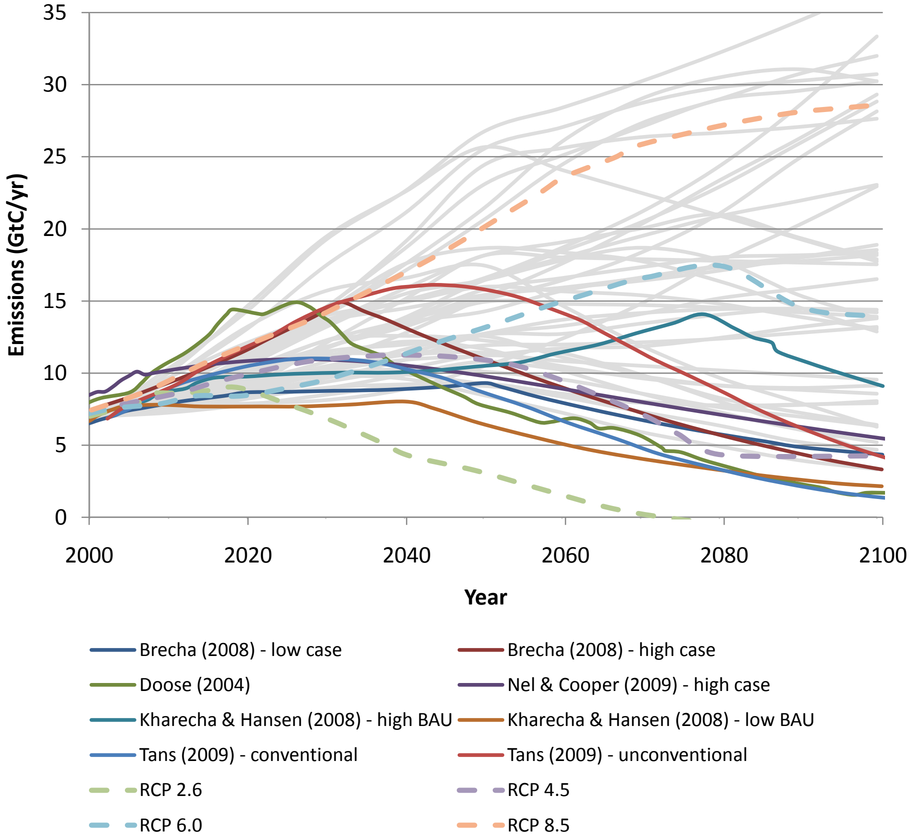

Fig. 2. Comparison between various published projections for emissions due to fossil fuel production against the RCP scenarios from Moss et al. (2010). The faint grey lines correspond to the 40 SRES scenarios presented in Nakicenovic and Swart (2000).

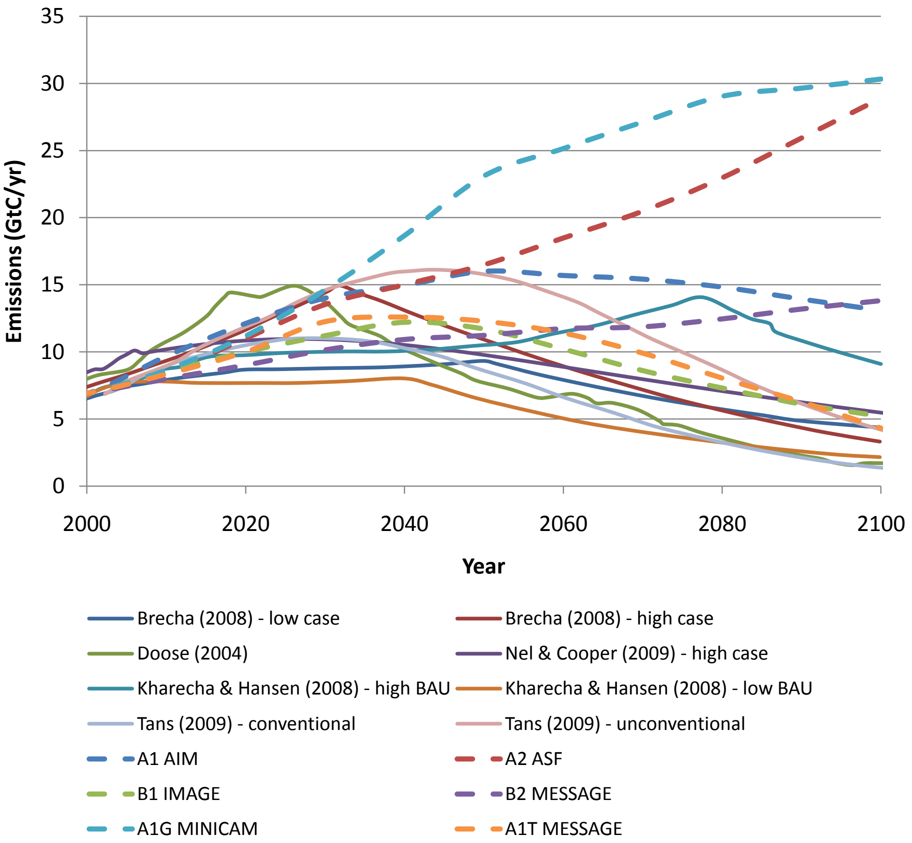

Fig. 3. Comparison between various projections for GHG emissions due to fossil fuel production and the six SRES marker scenarios presented in Nakicenovic and Swart (2000).

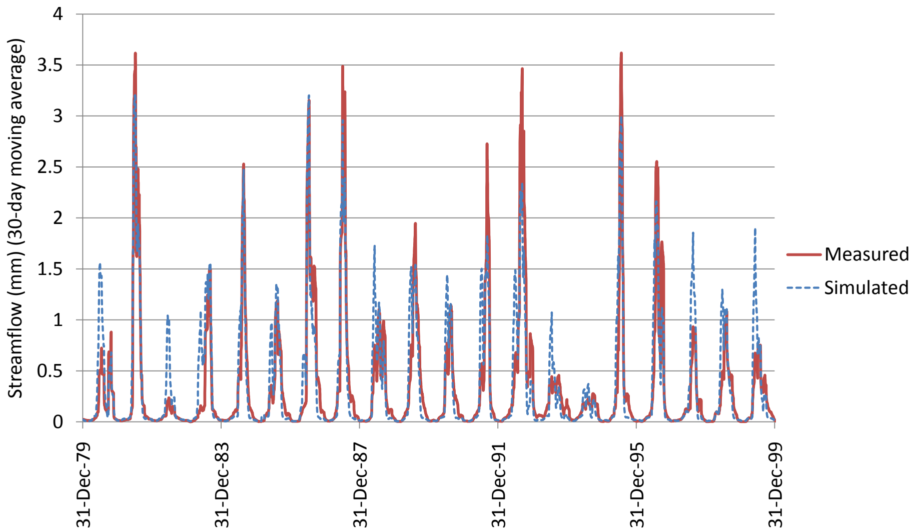

Fig. 4. Observed and simulated streamflows in the calibrated GWLF model.

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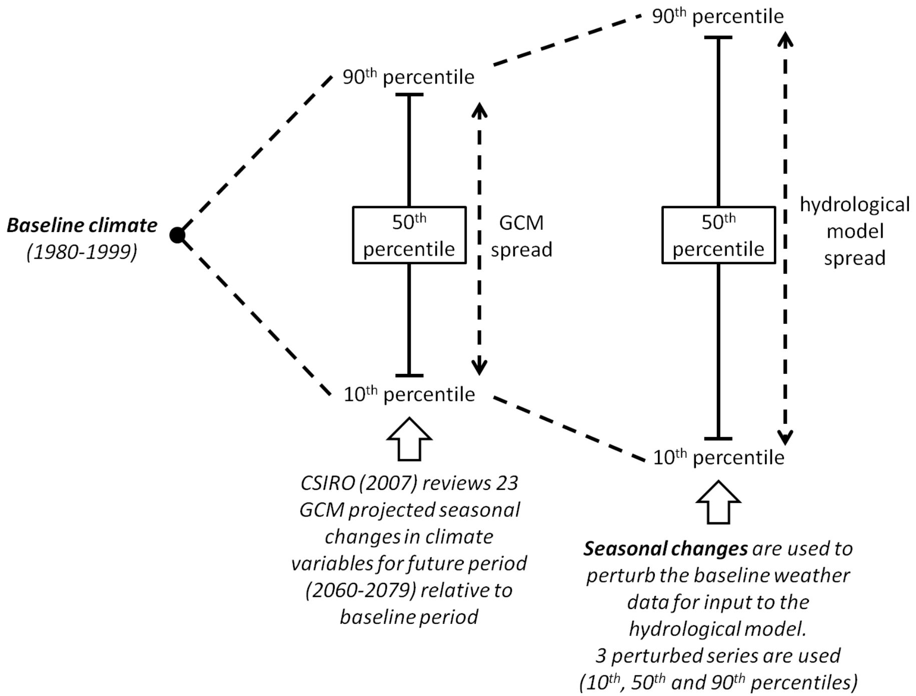

Fig. 5. Schematic showing climate scenario development and treatment of model spread.

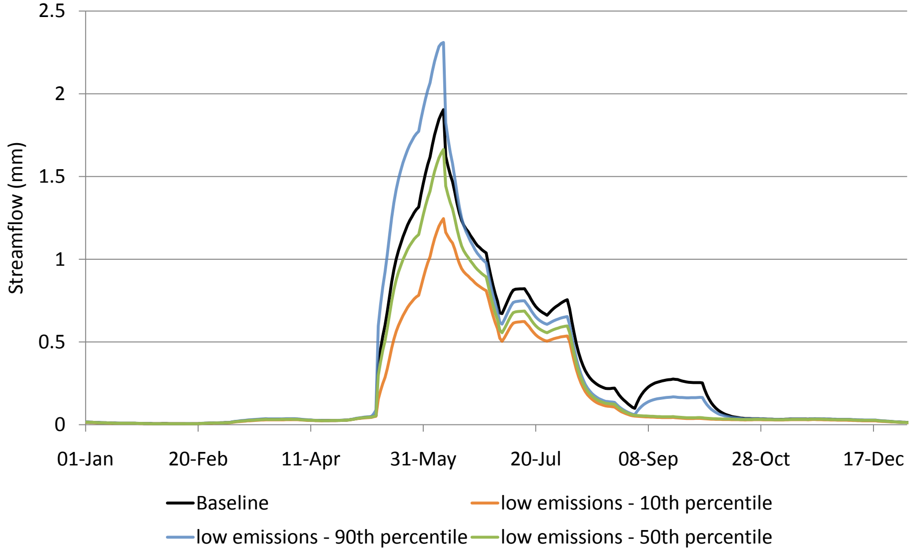

Fig. 6. One year time-slice (1999) of the hydrograph for baseline and low emissions scenario.

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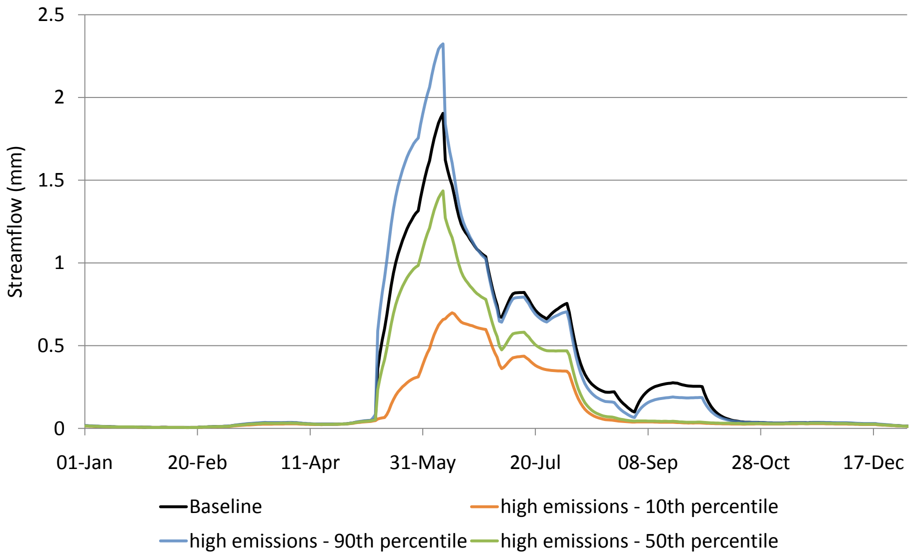

Fig. 7. One year time-slice (1999) of the hydrograph for baseline and high emissions scenario.