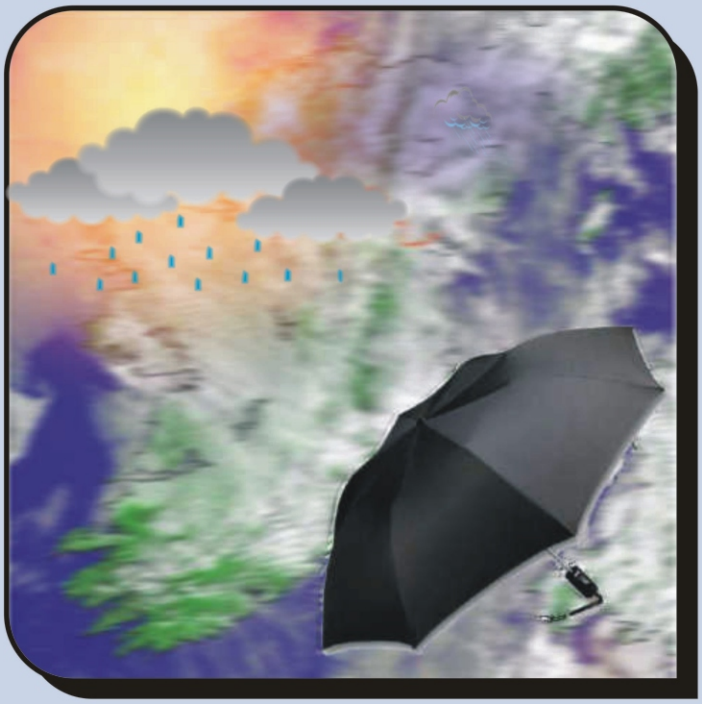
GREATER DUBLIN STRATEGIC DRAINAGE STUDY

REGIONAL DRAINAGE POLICIES
Technical Document



Volume Five
Climate Change

March 2005

NATIONAL DEVELOPMENT PLAN

Dublin Drainage
A Strategic Study for Greater Dublin

Volume One
Overall Policy Document

Volume Two
New Development

Volume Three
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1 EXECUTIVE SUMMARY

Climate change is of considerable concern to all professionals whatever their discipline as well as being a popular topic for general discussion. The water resources sector has been targeted as one of the key issues by academics and politicians as the expected impact on every day life is likely to be dramatic in many places around the world. This draws attention to the need to have an understanding of the likely change that will take place over the next 100 years in Ireland, particularly the Dublin region, in order to define suitable policies to take account of the changes these climatic conditions are likely to bring.

Ireland appears to be rather better off than many countries, both in terms of resources and also the expected limited impact of climate change compared to many other countries. In fact the layman would generally regard the projected changes as acceptable, even desirable, with drier summers and warmer throughout the year. However there are challenges for drainage professionals which, if not suitably catered for, will have serious impacts on key issues affecting the prosperity and living conditions of the community.

This report provides a technical overview and recommendations of the relevant issues for drainage engineers. It is based on selecting the A2 (Medium – High) scenario of the UKCIP02 models. A2 has been selected as the precautionary position based on the official view that no one scenario is more likely than another. However reductions in greenhouse gases achieved over the last decade do not suggest that lower growth projections would be appropriate. Growth scenarios are explained in Appendix B. The appendices provide the wider context of the various climate change scenarios and give a feel for the range of predicted changes that may occur.

1.1 Rate of Climate Change

The debate on whether environmental changes are taking place due to the man’s activities and the direction of these projected changes is now virtually unchallenged. Ireland has already recognised the reality of this situation, through its involvement in the Kyoto Protocol to control emissions on greenhouse gases, and the establishment of the National Climate Change Strategy (NCCS) to manage the process.

The current debate relates to the accuracy of predictions and their implications. There are quite a number of climate change models and each are run with a number of scenarios and these result in a wide scatter of predictions. However this helps draw attention to the level of uncertainty and the need to take a precautionary and flexible response to the impending changes.

The figures provided in this summary are taken as rounded values based on the A2 (Medium - High) climate modelling scenario. Ranges and values from other SRES scenarios have not been given to assist clarity. There is extensive documentation from the UKCIP programme available for those interested in gaining a more detailed insight on the subject. The NCCS predictions that have been made are reported in Appendix C.

1.2 Climate Change Model

There are quite a number of GCM (General Circulation Models) of the world climate. The Hadley model and their RCM3 model results have been used for this report. The models have not been specifically run for the GDSDS project. The Hadley model is generally regarded as a “good” model on the basis that it predicts current climate quite well and its results are used for all aspects of climate change impact across the UK.

The GCM model is used to provide boundary conditions to the Hadley Regional Climate Model (RCM3) which carries out a more detailed analysis for Europe using four CO_2 “forcing” scenarios; Low, Medium, Medium-High, High. These scenarios are selected from a set of scenarios derived from an international evaluation of CO_2 and other gas emissions projections. The previous Hadley RCM2 model, which was based on the UKCIP ‘98 GCM results has recently been superseded by the RCM3 output and UKCIP02. The predicted changes for the future are significantly different, generally indicating less rainfall than that predicted by the earlier model.

Although the UKCIP02 results are therefore assumed to be the most relevant and accurate, the difference between the '02 and '98 results are viewed as illustrating the degree of uncertainty in predicting future weather, rather than suggesting that the '98 data are incorrect.

1.3 Temperature

There are two key features that are of particular interest to drainage engineers in setting their criteria and designing appropriate solutions. These are rainfall and sea level. Temperature change is the most certain of the parameters, which is predicted by the models. This is because of the relatively straight forward relationship between CO_2 and other gases and aerosols to solar radiation compared to the processes involved with rainfall.

Temperature is not really directly of concern to drainage engineers, but it is the principle cause for sea level rise due to thermal expansion of the oceans as well as affecting glacier and snow melt rates. It increases the energy available for storm events, which is why there is an expectation of more intense rainfall. It also has an impact on evaporation (and therefore lower base flows in rivers) and elevated river water temperatures. The predicted range of temperature is wide. Figures for Ireland have not been seen, but the UK has experienced a rise of 1^0C over the last century and is predicted as rising by a further 3^0C +/- 1.5°C by the end of this century. These figures are very large in global terms, even though the values do not appear to be so when compared with normal daily temperature fluctuations.

- Annual average temperature increasing by approximately 3 degrees by the year 2100

1.4 Rainfall

Rainfall changes are of direct interest to drainage engineers. Flooding and other issues are directly a function of rainfall. The drainage engineer is actually little interested in annual rainfall totals, and is much more concerned with daily and hourly periods for rare events. Unfortunately even the RCM climate models have limited resolution, both temporally and spatially, and therefore there is considerable uncertainty in determining the values of specific concern which will enable engineers to carry out analysis of systems.

The UK Climate Impacts Programme 2002 (UKCIP02) suggest the following changes in rainfall for the A2 scenario. The model shows that seasonal affects are different with winter rainfall depths becoming 20 percent greater and summers getting drier by 35 to 45 percent. The range of predictions for summer is considerably greater than those for winter.

The 2 year daily rainfall event generally shows similar trends with a 20 percent increase in winter and 10 percent less in summer. This means that, in time, the current time series rainfall will not be representative and should be replaced with a stochastic series for the future which is particular to the Dublin region.

Daily data from the Hadley RCM3 model for the Dublin region has been analysed under the GDSDS project suggesting that the 2 year return period event has an increase of around 10 percent, rising to nearly 25 percent for the 100 year event. This results in a significant reduction in the return period for any event of a given depth. However the findings by Maynooth are less extreme (see appendix C) with little change in rainfall predicted for the East coast. Extreme care should be taken in applying these results in the light of the accepted uncertainty of predicting future rainfall. A precautionary position is proposed of applying a 10% uplift to design rainfall until additional work is carried out in this area.

There is no hourly rainfall information currently available from the Hadley model. As this duration is of particular importance to drainage engineering, a decision must be made with regard to this level of resolution even if there is considerable uncertainty in any approach used to derive these values. As the information on this process is so sparse it is advised that the current criteria is related directly to the daily data information and to re-visit the issue of short duration rainfall when more knowledge exists.

It should be noted that the spatial resolution of 50km square used in the model results in considerable smoothing effects. Thus ratios between point rainfall and spatially averaged rainfall are needed. These scaling factors are likely to be a function of the duration of the event. The climate change models provide little assistance on this issue and methods developed in the Flood Studies Report (FSR) have to be applied.

- The current time series rainfall should be factored on a seasonal basis
- Design rainfall events depths should be factored by 10%
- A stochastic future time series rainfall should be developed for the Dublin region

1.5 Sea Level

Sea level has four components to consider for engineering application. These are:

- rate of sea level rise
- rate of land fall / rise
- surge height
- wave height

The projected increase in temperature will cause expansion of the water column and result in an increase in sea level. The change in storm conditions will also affect surge and wave heights, the latter also being affected by the increase in water depth. Finally the land surface levels of Ireland are changing slowly due to recovery from the ice age with the north rising and the south sinking. The Dublin region is understood to be sinking at 0.3mm per year over the last century. The predicted rise in sea level in the UKCIP02 model, taking into account surge, by the end of the century, is in the order of 300mm to 400mm with an additional 30mm due to the relative land movement. Due to the very slow process of expansion of the oceans, it should be noted that this trend in increased water levels will continue for up to 1000 years resulting in sea level changes of between 1m to 3m depending on a range of assumptions. Work carried out by Maynooth which looked at eight GCM models predict a sea level rise change of 480mm for the end of the century. The difference between 400mm to 480mm represents 16 years at 5mm/year and is small relative to the uncertainty of sea level prediction by 2080 – 2100. The selection of 400 to 480mm for a design criterion, is recommended based on the view that the design life for any structure, including drainage is rarely greater than 100 years.

The affect of wave height is primarily an issue for sea defences and is not particularly a concern of drainage engineers or the GDSDS. Currently there is a major coastal defence study which will be addressing risk in the coastal zone and the development of a tidal surge early warning system.

There is one other issue that needs to be considered. As water levels rise, the freeboard against flooding will reduce (subject to engineering activities). However this will lead to a much greater importance of assessment of return period events where river water levels or surcharged sewer levels interact with high tides. This means that design must take account of joint probability of rainfall and high sea levels and the dependency of both with regard to storm events. At present it is not known what the level of dependency is in the Dublin region between the joint occurrence of both events, but it is likely that there is some. A detailed statement on a method of approach is provided in appendix D of this document. However, a pragmatic approach based upon a combination of tides and river flow return period is also recommended to allow analysis of many drainage needs to be made without having to carry out a joint probability analysis. The level of dependency of the joint occurrence of both events can range widely and a study to determine the degree of correlation is likely to be needed on this subject at some stage.

The recommendation regarding criteria for flooding related to sea level rise is to use a 200 year criterion on the basis that flooding from the sea tends to be catastrophic. The sea level for the 200 year event, based on historic records, is a level of 2.89m. However as the February 2002 record water level was 2.95m, it is suggested that cognisance is given to the fact that this event occurred and that extrapolation of the historic data set to 200 years is, by definition, going to have some degree of error. It is therefore suggested that the precautionary position is to use 2.95m +

0.4m or 0.48m for the design criteria for the future. This, at 1 decimal place based on the realistic accuracy of prediction, is 3.4m.

An even higher sea level criterion may be needed for two reasons. The first is that the consequence of inundation from the sea varies and certain areas such as Ringsend sewage treatment works might justify this. The second reason is the long term strategic planning of the Dublin area. Dublin has existed for several hundred years and is likely to continue to be the focus of the country for many centuries to come. With the knowledge that sea level rise in the very long term could be between 1 and 3 metres, adaptive long term planning of key aspects of the Dublin area should take this into consideration. It is suggested that for these issues that 2.95 + 1.0m be used. Applying the same logic of realistic precision, a value of 4.0m is proposed.

The next decade should see greater certainty and improved science in the prediction of sea level due to climate change and this will lead to re-appraisal of policy and design parameters.

- Sea level design criteria must take into account that sea levels are forecast to rise for several centuries. Strategic planning of the Dublin area should take an appropriate precautionary position
- Pragmatic combinations of return period events have been recommended for areas where joint probability has to be considered
- Complex or expensive solutions to joint probability problems should refine the analysis using a joint probability methodology

1.6 Groundwater

Groundwater changes are going to reflect the drier summers and wetter winters. However predictions are catchment specific and would therefore need to be derived from a detailed analysis. The importance of groundwater changes for drainage policy is limited to the change in being able to use infiltration techniques and the exfiltration/infiltration of flows into structurally defective sewers.

The use of infiltration techniques (soakaways) is normally a function of soil type and antecedent rainfall conditions rather than groundwater level changes.

The infiltration and exfiltration into and from sewers through joints and cracks is primarily a function of the sewer structure. Again the flow rates involved are usually more a function of antecedent rainfall rather than the groundwater level.

1.7 Implications of Changing Drainage Criteria

The degree of certainty for various aspects of climate change varies depending on the parameter of interest. Sea level change is certain, but the rate of change is slightly less clear. Nevertheless all relevant organisations are or should be taking appropriate precautionary action. The implications of applying the change in sea level criteria will be very significant in low lying areas in terms of sea defence. The consequence of tide locking is linked to the duration of time in which the tide affects the outfall. The implications with regard to drainage solutions will be to slowly reduce the level of service provided by the drainage system as an increase in sea level occurs. To maintain the same degree of service will result in additional storage being built. The degree of additional storage needed will be dependent on the duration of tide locking and the ground levels being drained.

The degree of certainty with regard to the level of hydrological change is acknowledged by all experts as being quite low. This is particularly true for extreme events that are critical for drainage design application. The implications of applying between 10 and 25 percent uplift on design rainfall will significantly increase solution costs to deal with existing flooding and spills. These costs (very approximately) will rise by up to 50 percent compared to applying current criteria. The cost of construction of new pipework will also rise, but probably only in the region of 15 percent. The uncertainty of the change in rainfall, together with the knowledge that these changes are predicted to take place over the coming century implies that solutions needed to address system failures (failures to meet trigger criteria) should be approached in a flexible manner. Any solution on the existing network should at least meet target criteria based on current rainfall, but whether it satisfies future rainfall conditions, should be based on cost – benefit considerations. The consequences of failure should be a specific consideration in scheme development and selection.

A qualitative view on the level of uncertainty in order of decreasing certainty for the relevant parameters for drainage is as follows:

- average temperature increase
- sea level increase
- wetter winters
- drier summers
- increase in extreme rainfall intensities and depth

1.8 Application of Criteria for Detailed Design

The increase in rainfall should be applied to all durations for any return period. Current tools produce design events for the current climate. To apply the climate change criteria, the intensity values of these hyetographs should be factored. (Factoring hyetograph intensity values by 10% will result in the rainfall depth increasing by 10%). Due to cost implications and uncertainty of future rainfall, the current position will be to apply a uniform factor of 1.1 (10 percent) to all design rainfall events for all durations and all return periods. This is considered to be a reasonable precautionary position which will be reviewed in the light of further output from authoritative experts in the future.

The design of new drainage can readily accommodate these recommendations by using bigger pipes. Existing infrastructure will indicate increased flooding and a reduced level of service. As with all proposals for rehabilitation, the decision to improve the system is based upon the reduced level of service, the consequences of "failure" and the cost of addressing the problem. Changes to existing systems will only occur on an individual basis as they are deemed appropriate. The criteria proposed allows the investigation of potential problem areas. Due to the uncertainty of the rainfall recommendations, major rehabilitation works will be assessed using the advised future rainfall, but will be designed using a sensitivity approach and risk evaluation to arrive at an appropriate cost benefit solution. Rehabilitation schemes should not be triggered by the predicted reduction in level of service due to climate change and should only be considered when its performance is actually deemed to be inadequate.

The concept of very long term planning for sensitive areas (a 1m rise in sea level) would apply to Ringsend sewage treatment works (on the low lying Dublin peninsula) and other locations where the implications of a change in strategy (closing the works) cannot be envisaged as a feasible option in the foreseeable future.

The official Dublin Port gauge is used for sea level values. It is important to take account of the increase in water level further up the estuaries.

- Climate change rainfall multiplier 1.1 applied by factoring rainfall intensity values for design of new structures
- Rehabilitation of existing structures should be evaluated on the basis of current performance
- Scheme design and selection should be based on risk and cost – benefit analysis. Consequence of failure, due to uncertainty of future rainfall, should be specifically taken into account

1.9 Irish Climate Change Policy

This Policy Report has reviewed currently available information on climate change, both globally and locally. Currently the emphasis is on the wider issues relating to climate change and in particular the issue of addressing greenhouse gas emissions. Policy specifically addressing climate change with respect to drainage related aspects has yet to be produced.

The EPA sponsored project carried out by NUIM is involved in reviewing policy on climate change and their findings have been considered and taken into account in this document.

This climate change policy report for GDSDS covers all the principal effects of climate change on the Greater Dublin Area (GDA), in terms of the main factors affecting drainage, particularly sea level and rainfall. The Policy Report proposes modification factors for drainage engineers to apply to their usual design parameters. The process of agreeing criteria and determining Climate Change Policy is proposed as follows:

- Consider the cost implications of these proposed criteria against the benefits provided, together with the level of uncertainty of the various climate change projections;
- Discuss and agree with local authorities the approach and parameters to be adopted by drainage engineers to take account of Climate Change, based on this Policy Report;
- A periodic review of the GDSDS Climate Change Strategy should be made following any reviews carried out by NCCS.

The debate over taking a precautionary position with uncertain information and the cost implications is one that can only be decided by those making decisions. The reverse position may also assist by considering the acceptability of the consequences of a potential reduction in the level of service provided.

1.10 Recommendations

The accuracy of climate models is known to be limited, particularly with regard to issues related to drainage such as rainfall. However as nearly all measures of the various relevant parameters affecting drainage are believed to be negatively affected, it is important to take a precautionary stance on all drainage criteria. Climate change models will continue to improve and, in due course, these criteria will need to be revisited and revised as appropriate.

The following points summarise the recommendations on drainage criteria to be applied in the Dublin region made through this report.

1. The results of the Hadley Centre RCM3 model are to be used for climate change policy for the Dublin region.
2. The UKCIP02 Medium – High (A2) SRES scenario should be used for climate change policy.
3. The projections for 2080 – 2100 should be applied to all infrastructure design unless design lives are considered to be short (30 years or less). Linear interpolation of the recommendations might then be applied.
4. Sea level rise for 2080 in the Dublin region will be assumed as being between 400mm to 480mm.
5. The 200 year return period should be used for coastal flooding design and this level is 3.4m Malin AOD. Strategic very long term Dublin area planning and highly sensitive areas to use 4.0m AOD.
6. The design sea levels refer to the Dublin Port gauge and higher levels will occur up river estuaries.

7. A pragmatic approach to joint probability analysis for combinations of events can be taken initially, but more detailed joint probability analysis should be applied (see appendix D) where costs are significant or other reasons require greater accuracy in assessing performance or flood risk. The following event combinations are proposed based on providing combined return periods greater than 100 years for river flooding affected areas and 30 years for flooding from sewerage systems affected by river or tidal levels.

   River flooding evaluation (100 years):

   - MHWS tide with 100 year river;
   - 1 year tide with 5 year river;
   - 5 year tide with 1 year river.

   Sewer system flooding evaluation, with tides (30 years):

   - MHWS tide with 30 year drainage;
   - 1 year tide with 1 year drainage;
   - 5 year tide with 0.25 year drainage.

   Sewer system flooding evaluation, with rivers (30 years):

   - 0.25 river with 30 year drainage;
   - 1 year river with 5 year drainage;
   - 5 year river with 1 year drainage.

8. In cases where there is a potential for life threatening situations to develop from rapid inundation due to breach of sea or river defences, then a standard of protection greater than the 1:200 year event should be considered. This may be as high as 1:500 or more depending on the level of risk involved.

9. River flow changes in the future should be determined individually for catchment planning. However for the purposes of CSO drainage system performance evaluation, the following precautionary position should be taken.

   - River baseflows could reduce by as much as 40%.
   - River flood flows are likely to increase by around 20%

10. Present day design rainfall depths for all durations and return periods are to be increased and factored by 1.1.

11. A new time series rainfall should be produced which represents future rainfall conditions.

    11.1 Present day time series rainfall are to be modified separately for summer and winter series:

    - Summer rainfall intensities to be factored by 0.9, except for the top 5 events
    - The number of summer rainfall events is to be reduced by 40%.
    - Winter rainfall intensities to be factored by 1.10

11.2 It is recommended that a future stochastic rainfall time series should be produced in the medium term to properly reflect the projected change in seasonal rainfall pattern across the Dublin region.

12 New drainage schemes should be evaluated using these recommended criteria but should also carry out risk and cost – benefit analyses. The consequence of “failure” should specifically be considered and may well influence scheme selection due to this uncertainty. However major rehabilitation or modification of the networks should still be based on evidence of need rather than the predicted reduction in level of service.

13 Explicit advice is not provided on issues relating to changes in infiltration, and other secondary effects that are likely to occur due to climate change. All these issues (discussed in chapter 2) should be considered and allowed for, if thought appropriate, when designing drainage schemes.

14 Ireland should decide whether to rely upon the UKCIP (or other modelling) work in the future, or carry out work on climate change modelling to support its policies dealing with future change.

15 Rivers and their quality are a very important issue for Ireland. The uncertainty with regard to river flows has far reaching implications for Ireland (water resources, fisheries, tourism) and although this document is focused on drainage issues, it is suggested that a climate change evaluation and policy is needed to address these issues.

16 The dependency for joint probability analysis between tide, river and rainfall events should be evaluated to enable a better understanding of the level of service being provided. This is important as tide levels will have an increasing influence on drainage for important areas of the Dublin region.

2 CLIMATE CHANGE DEBATE

2.1 International Opinion

The Intergovernmental Panel on Climate Change (IPCC) has concluded that most of the warming observed over the last 50 years is likely to have been because of increasing concentrations of greenhouse gases due to human activities.

The most useful index describing the state of global climate is the average surface air temperature of the planet. Estimates of this index are compiled from millions of individual thermometer measurements taken around the world and which date back to 1860. The records show that global temperature has risen by about 0.6°C since the beginning of the twentieth century, with about 0.4°C of this warming occurring since the 1970s. Figure 2.1 shows the annual differences in temperature, compared with the average temperature between 1961 and 1990.

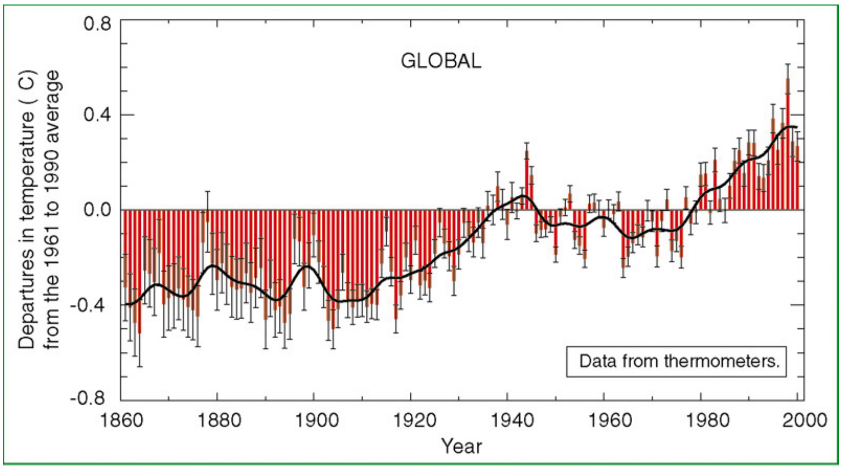


Figure 2.1 ***The Observed Increase in Global-Average Surface Air Temperature (Differences in temperature are relative to 1961-1990 average)***

The year 1998 was the warmest in this 142-year record, and 2001 was the third warmest. The decade of the 1990s was, globally, the warmest decade in the last 100 years, and it is likely that the last 100 years was the warmest century in the last millennium.

Other evidence for changes in global climate include:

- an increase in night-time temperatures over many land areas at about twice the rate of day-time temperatures increases;
- an increase in the length of the freeze-free season in many Northern Hemisphere mid-to-high latitude regions and a lengthening of thermal growing seasons;
- more intense rainfall events over many Northern Hemisphere mid-to-high latitude land areas;
- a near world-wide decrease in mountain glacier extent and ice mass;
- a decrease in Northern Hemisphere sea-ice amounts and a substantial thinning of Arctic sea-ice in late summer.

2.2 Local Opinion

Information from analysis of Irish climate change is limited. However extensive analysis of the weather of UK has been carried out and, due to its proximity, it seems reasonable that Ireland has and will experience similar changes. It is important to realise that the UKCIP98 and UKCIP02 results are from models that include Ireland and much of mainland Europe and are therefore relevant to the Dublin region. The main limitation is related to the lack of detailed analysis of the output over the Dublin area so it is useful to extrapolate some information from analyses carried out for the UK.

The UK climate has also changed over the last century, with central England temperature rising by almost 1°C. The decade of the 1990s was the warmest in central England since records began in the 1660s. Average sea level is currently (this last decade) rising by about 1mm per year and winters across the UK have been getting wetter, with a larger proportion of the precipitation falling on heavy rainfall days.

It is generally believed that further climate change is inevitable. This is because much of the change in climate over the next 30 to 40 years is already determined by past and present emissions of greenhouse gases and by the inertia of the climate system. On the other hand, the climate of the second half of the twenty-first century and beyond will be increasingly influenced by the volume of greenhouse gases emitted over the next few decades.

Based on this belief in the existence of climate change, it is apparent that a climate change policy is relevant for Ireland and thus it is important to determine criteria to enable engineers to design for these changes. Before defining these criteria, it is pertinent to summarise the basis of the results currently predicted and to try and understand the level of uncertainty and range of values.

2.3 Climate Change Models

It is not intended to describe here the detailed mechanisms of climate models. In summary there are a number of Global Models used around the world, of which the Hadley Model, HadCM3, is the one used by UK. It is generally regarded as being a good model on the basis of its good representation of current climate. The results it predicts for the future are generally corroborated by the results obtained by a number of other GCM models. The Hadley centre has a regional climate model (RCM) which is run for higher resolution detail which uses the GCM model to provide boundary conditions. The results of the Hadley work have been used to report on predicted climate changes in the Dublin area.

The UK Met Office Hadley Centre models, used as the basis for the UKCIP02 scenarios, have been developed over many years and have been extensively validated. It is important, however, to appreciate the uncertainties involved in modelling global climate, because these also influence the confidence we have in higher resolution regional results, such as those used for the UKCIP02 scenarios. Currently, the only way to appreciate this uncertainty is to look at results from the full range of global models that have been presented in the recent IPCC assessment. Whilst comparing different model results is important to illustrate uncertainty, there is no easy way to attach higher or lower confidence to the results of one model over another. The Hadley Centre models, however, perform well in representing current climate and therefore provide credibility for its predictions for the future.

All models agree that, over the UK, winters will become wetter and warmer. There is not quite the same agreement about changes in summer. A majority of the models indicate less rain, but more consistently in the south of the country than in the north. The Hadley Centre model simulates changes close to the middle of the models range for winter, but shows a greater decrease in summer rainfall than most models.

2.4 The Emissions Scenarios

Climate changes in the future depend on future emissions of greenhouse gases and other pollutants, which in turn depend upon how population, economies, energy technologies and societies develop. The intergovernmental Panel on Climate Change Special Report on

Emissions Scenarios (IPCC SRES) developed a range of projections of possible future emissions. Four of these have been chosen (designated B1, B2, A2 and A1FI) which span nearly the full range of projections. The amount of carbon emitted over the twenty-first century under each of these emissions scenarios is shown in Figure 2.2. Summed over the century, A1FI has the highest total emissions (2189 giga, or billion, tonnes of carbon (GtC)), more than twice the mass of the lowest scenario, B1 (983 GtC). The atmospheric concentrations of carbon dioxide by the 2100 resulting from these emissions are shown in Table 2.1

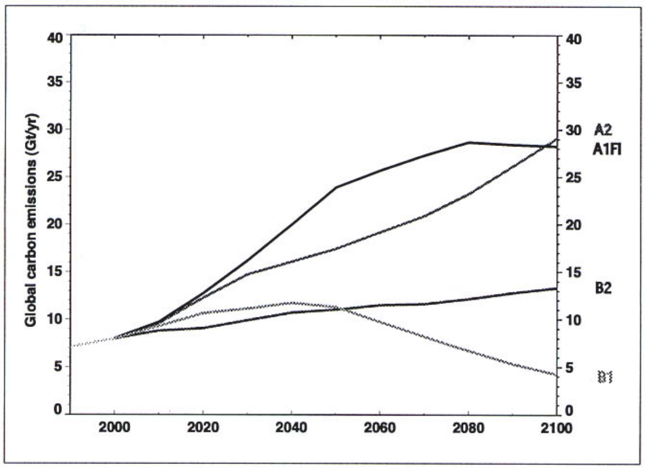


Figure 2.2 Global Carbon Emissions from 2000 to 2100 for the four chosen SRES emissions scenarios. Observed data to 2000

2.5 The Climate Models

The Hadley Centre global climate model was used to simulate changes in climate due to each of these emissions scenarios. Results from the global model for the SRES A2 emissions were then used, via a further stage, to drive the regional version of the model, which has a resolution of 50 km over Europe. Results from these regional climate model experiments formed the UKCIP02 Medium-High Emissions climate change scenario. Three further climate change scenarios were generated from these same model results using pattern-scaling methods and are labelled Low Emissions, Medium-Low Emissions, and High Emissions, corresponding respectively to the B1, B2 and A1FI emissions scenarios. The Hadley Centre global model simulates warming for the A1FI emissions scenario that, by the 2080s, is about twice as great as for the B1 scenario. The predicted temperature changes and CO_2 concentrations are shown in Table 2.1. Carbon dioxide concentration in 2001 was about 370 parts per million (ppm). No probabilities can be assigned to these four scenarios and they should all be regarded as plausible future climates.

Even if global emissions of carbon dioxide eventually fall below today's level, as assumed in the UKCIP02 Low Emissions scenario, the future rate of global warming over the present century would be about four times that experienced during the twentieth century. If the emissions rate increases to approximately four times today's level – as for the High Emissions scenario – the future warming rate would be about twice as rapid again.

SRES Emissions Scenario	UKCIP02 Climate Change Scenario	Increase in Global Temperature (°C)	Atmospheric CO_2 Concentration (ppm)
B1	Low Emissions	2.0	525
B2	Medium-Low Emissions	2.3	562
A2	Medium-High Emissions	3.3	715
A1FI	High Emissions	3.9	810

Table 2.1 Changes in Global Temperature and Atmospheric Carbon Dioxide Concentration for the 2080s Period (2071-2100 average)

The Hadley regional model is the only one to have been run for the current set of forcing assumptions and therefore corroboration is not available to confirm the results in the same way. The Regional Climate Model (HadRCM3) provides a resolution at 50km, compared to 265km, thus enabling a more detailed regional picture to be obtained. It uses boundary conditions from the GCM runs to carry out the more detailed analysis. The UKCIP02 results are based on 3 runs for the A2 scenario and one run of the B2 growth curve. The results are then scaled to provide the Low, Medium and High predictions. This means that there is an additional degree of uncertainty for the predictions except for A2 (the Medium-High prediction).

Although the spatial resolution is much improved it should be understood that there are some processes like convective storms, which are smaller in scale than this and therefore the effective modelling of these processes are less likely to be well replicated compared to frontal weather systems. This is an important issue for drainage engineers. In addition to the spatial resolution, which will smooth extreme values for point measurements, there is the temporal aspect also to consider. The RCM model uses a time step of 5 minutes, but due to data volume, this information is not stored. Information has been processed and detailed for daily values. The resolution actually stored is hourly but this has not been checked and will be unavailable for general public consumption for some time. It is understood that validated 6 and 12 hourly values exist for the UKCIP98 runs and that a sample of daily data information from the UKCP02 model has also been validated.

2.6 UKCIP Scenarios 98 / 02

The UKCIP02 scenarios replace the climate scenarios published for the UK Climate Impacts Programme in 1998 (the UKCIP98 scenarios). The new scenarios have been designed to provide more detailed information about geographical variations across the UK and to provide more information about changes in extremes of weather and sea level. Even though more detail is provided in the new scenarios compared to those from 1998, the two sets of scenarios are qualitatively similar in many respects.

The difference in the scenarios not only reflects the changes / improvements to the Global Model boundary conditions and similar changes to the RCM model, but they are based on different forcing scenarios. The latest set of runs uses generally higher forcing CO_2 growth rates. The results of the latest model have been used in preference to the 98 results where they are available. However as more analysis has been carried out on the 98 data, there are certain data which can be used to support the projected changes that are likely to take place over Ireland.

The main differences between the predictions are:

The four UKCIP02 scenarios show slightly higher warming rates over the UK than the four UKCIP98 scenarios. This is partly because they are based on generally higher carbon dioxide emissions than in 1998, partly because the (warming) effect of reductions in sulphur dioxide emissions, and partly because the climate model used has a larger response to increased concentrations of greenhouse gas scenarios. On the other hand, the UKCIP02 scenarios show slightly *smaller* rates of sea-level rise than the 1998 scenarios. This is because of improvements in the way the thermal expansion of ocean waters and the dynamics of land glaciers are modelled, which suggest that sea-level rise is slightly less sensitive to global warming than was considered to be the case four years ago.

The UKCIP02 scenarios suggest that summers will become significantly drier across the *whole* of the UK and Ireland – not just in England and Wales – and by a larger amount than was the case in the 1998 scenarios. The winter rainfall is predicted to get wetter than the present day, with fairly close agreement with the '98 scenarios. The total rainfall over the year is predicted to be very slightly less than the present day. In general the latest model provides a drier picture compared to '98 results.

- UKCIP02 regional model results used for climate change policy
- Medium – High (A2) scenario to be used

2.7 Uncertainty of Model Predictions

The technical report for UKCIP02 provides high, medium and low levels of certainty to a whole range of indicators and also provides a suggested range of uncertainty to be applied to each scenario. It should be remembered that each forcing scenario is regarded as being equally likely, so the range of possible change is high.

The following relevant indicators and their certainty are shown in Table 2.2 which has been copied from a UKCIP02 report.

Indicator	Prediction	Confidence	Comparison with '98
Rainfall			
Winter daily depth	Increase	High	Fair
Winter season	Wetter	High	Good
Summer season	Much Drier	Low	Poor
Contrast between Summer and Winter	Greater	High	Good
Variability in winter and summer	Greater	Low	Fair
Soil Moisture summer and autumn	Decrease in SE UK	High	N/A
Soil Moisture winter and spring	Increase in NW UK	Medium	N/A
Sea levels			
Global average sea level	Rise	High	Fair
Global average sea level	9 to 69cm (4 scenarios)	Medium	Fair
UK average sea level	equal to global	Low	N/A
Surge levels	some areas tidal surges reduce	Medium	Fair
South East of UK surge levels	Maximum surge increase	Low	N/A

Table 2.2 Climate Change Indicators and their Confidence of Prediction

An indication of certainty of the predictions is also reflected in the range allocated to predicted changes. The values contained in Table 2.3 are suggested in the UKCIP02 report for any location in the UK.

Indicator	Range
Winter precipitation Medium-High	+/- 15 %
Summer precipitation Medium-High	+/- 30 %

Table 2.3 Climate Change Indicators

- Hydrological prediction of rainfall change has a low degree of certainty
- Sea level change prediction has a fair degree of certainty

2.8 Scenario Selection and Design Horizon

The four scenarios used for assessing future weather change are all stated as being equally likely, as the political direction of the future cannot be guessed at. In practice, it is necessary to take a view as drainage engineers and others need to work to a set of design criteria. This can be updated as new knowledge is gained, but a precautionary position requires the selection of criteria which take reasonable consideration of the possible future impact of projected changes, but which do not incur expenditure which cannot be reasonably justified. Unfortunately these two demands are difficult to marry up as the implications of any significant change in the weather is likely to require a significant change in criteria.

In keeping with many other projects investigating climate change, it is suggested that the Medium – High scenario be used as the basis for considering future change. It would seem prudent to take this scenario as there is little indication that the political will exists yet to make the changes necessary to radically alter CO_2 projections for the future. It should be noted that the lag effects of temperature change on the oceans means that future sea level rise is effectively certain over the next 100 years and only subject to the accuracy of modelling the rate of change. The hydrological changes are both less certain and have less built in inertia, but even this is measured in decades.

The design horizon must also be selected, as the “climate” is likely to be continuously changing. In practice the lifetime of any particular structure may be measured from a decade through to 100 years or more. Current economic assessment methods that use NPV tend to effectively indicate that anything beyond a 60 years criterion has little influence on option selection. However, if it is known that sea levels are to rise by between 1m and 3m over the next 1000 years, it seems that such methods are inappropriate in determining long term strategic Dublin area planning to safeguard the future for coming generations.

As the RCM2 model was run and results produced for the period 2080 – 2100 and RCM3 for 2070 – 2100, it would seem appropriate to use these results (effectively 80 to 90 years from now) as the datum for climate change. This is not only appropriate for many civil engineering schemes in terms of their likely life span, but also considerable analysis will be carried out over the next decade to refine and detail future climate for that period.

2.9 UK / Ireland Similarities

The HadRCM model covers most of Europe including Ireland. Results therefore exist for Ireland. However quite a lot of analysis of the UKCIP98 and UKCIP02 data has taken place over the last few years for the UK, but not a great deal on Ireland. Therefore it is necessary in certain instances to utilise this additional information where it helps to fill in any gaps or support tenuous decisions. The main areas in which this can be made use of are short duration rainfall and river flow analysis. It must be clearly stated that all such predictions are built on many assumptions and models that are hugely complex and therefore they must be treated appropriately.

Over the last 20 years, London has been used as a hydrological match to the Dublin region. This is largely based on the fact that the Annual Average Rainfall is very similar and both are east coast cities. However the use of London for Climate Change similitude is very inappropriate as can be seen at a glance at the UKCIP reports. This is due to the continental effect on London and the buffering effect of the Atlantic Ocean on Ireland.

A review of the RCM results across the UK and Ireland has been made and there is remarkable consistency between the Dublin region and the north east coast of England for many of the Climate Change indicators. Note that it is not the predicted values of the indicators that are to be taken, but the uplift change ratio applied to present day conditions that are normally reported.

It should be stressed that the recommendations made in this report are not based on this similarity. The point is being made to avoid the mistake of assuming London is an appropriate comparator for climate change in terms of hydrology. Daily rainfall data from the HADRCM3 model for the Dublin region has been obtained and the recommendations relating to rainfall in this report is based on this information.

2.10 Impact – Temperature, Sea level, Hydrology

Before selecting criteria to be applied to hydrological and other parameters, it is important to understand the impact of the various changes that are forecast to occur. Some are relatively obvious while others are less so. The selection of criteria needs to take account of the potential impact in conjunction with the cost implications related to a change in criteria.

2.11 Sea Level

Sea level change is a function of thermal expansion and ice melt. The projected increase by 2080 is around 300mm to 400mm (UKCIP02) which is slightly less than the figures projected in the UKCIP98 runs. However the thermal inertia of the oceans is so great that the CO_2 change that has taken place to date will continue to increase the sea level over the next 1000 years and will increase by between one and three meters. The level of certainty of this fact is accepted as being quite high. The main uncertainty is the rate of ice sheet melt that provides the wide range of water levels in the scenario predictions.

However sea level is not a constant as surge levels are related to storm cells and wind effects. The projected change in surge behaviour in the English Channel is considerable, but this is not reflected in the Irish Sea where it is not projected to be significantly different to the present day. This means that the difference in sea levels will be the same when considering any return period.

However, there is a growing body of concern within Ireland that believes that the UKCIP02 model may under predict easterly winds in the Irish Sea. An analysis of 8 GCM models (Maynooth 2003) predicts an average 480mm rise in sea level and they would prefer that this figure should be used for more extreme predictions of sea level.

The impacts of an increased level of the sea are relatively obvious, but are worth summarising. These are:

- Wave height and power
- Increased tide locking of outfalls
- Increased pumping costs
- Increased infiltration to sewers (close to the shore)

The principal problem is the issue of sea defences, which is not strictly within the scope of drainage criteria, but must be taken into account by coastal defence engineers. The increased depth of water allows waves of greater magnitude and strength and therefore defence design needs to be modified to meet this problem. The issues of increased infiltration, particularly saline inflows, and increased pumping costs are important for drainage engineers to consider, but are not likely to be of great significance compared to other climate change aspects.

- Sea level rise of 400mm to 480mm for all return periods for 2080 – 2100 (without allowance for land level change)
- Surge behaviour in the Irish sea is likely to be similar (UKCIP02) or increasing (Maynooth 2003) to that which exists in the present day

2.12 Land Level Changes

Ireland, like England and Scotland, is recovering from the ice age with land levels slowly adjusting from the loss of the ice sheet in the north. The Dublin region is believed to be falling at a rate of 0.3mm per year. Therefore over 100 years this amounts to another 30mm which needs to be applied to current design criteria.

- Land level drop of 30mm for 2080 – 2100

2.13 Sea Level and Rainfall Joint Probability

The primary issue of concern for drainage engineers is the increase in time of drainage systems being tide locked, especially where ground levels are lower than the sea level for short periods. The design of drainage structures is usually based on a certain return period, typically 100 years or more for coastal defence situations. As the sea level rises, the issue of joint probability of rainfall events and sea levels becomes more of a problem and the usual simplistic assumptions made are generally over-conservative. Typical examples are the use of a 100 year event of one against a 2 year of the other and take the worst case for design. A precautionary approach using a simple set of criteria is desirable, but it is also important to develop a good understanding of the realistic design return period being applied as solutions may be very expensive and these need to be justified against a realistic risk assessment of failure. The example used actually has a level of service that is in the region of 1000 years (and is a function of the degree of independence between the two events occurring).

To do a true joint probability evaluation of tide and rainfall risk requires an understanding of the dependency that exists between these events occurring simultaneously. It is known that there is some dependency in the Irish Sea and it is thought that the dependency coefficient is likely to be in the order of 10 to 50, but may be more. Currently there is a joint probability exercise going on for the whole coast of the UK that is due for completion by 2003. Unfortunately there appears to be little opportunity to use this information for the Dublin region, as these functions are highly regional and cannot be applied to other locations.

- Detailed joint probability analysis should be used for storage where solutions are very expensive
- Simple combination of events for pragmatic assessment of joint occurrence should be used for outline design and inexpensive schemes
- The level of dependency between rainfall, river flows and tides needs to be established for the Dublin area

2.14 Rainfall and Temperature

The predicted changes in rainfall are for wetter winters and drier summers and that all periods will become warmer. The daily rainfall events in winter will also tend to be larger. The summer situation is less clear as the UKCIP02 results suggest that daily rainfall events will be smaller and the summers much drier, but the UKCIP98 results suggest that the daily events might be slightly greater with summers being slightly drier.

What is of concern to drainage engineers is the short duration extreme event rainfall, in the region of 30 minutes to 6 hours. Unfortunately little analysis has been carried out on this and the limitations of the RCM model with its 50km grid makes it unsuitable for dealing with the detailed hydrological processes relevant for these type of events which tend to be spatially quite constrained. Extrapolation of the UKCIP02 data would suggest that these summer events might also be smaller. However there is clearly a relationship between temperature and summer thunderstorms. Since it is accepted that the most certain aspect of climate change is the increase in temperature that will take place, it is considered unwise to assume that summer thunderstorm events will become any smaller.

The impacts of these predicted changes are:

- Higher infiltration levels in winter
- More flows to treatment in winter
- More pumping costs in winter
- Sewers surcharged for longer leading to increased deterioration of sewers
- More spills from overflows in winter
- More polluted spills in summer from long dry inter-event periods
- More flooding in winter
- Possibly more localised flooding in summer
- River water levels lower in summer
- River water levels higher in winter
- River water temperatures up in summer
- More water frequent flooding of flood plains

All these issues should be considered and allowed for if thought appropriate when designing drainage schemes.

2.15 Impacts of Climate Change

The predicted impacts of climate change on winter and summer characteristics are described below.

2.15.1 Wetter Winters

The longer wetter winters will result in raised ground water levels. This will result in extended infiltration and rainfall related ingress. Sewers which suffer from infiltration, particularly foul sewers, will have reduced capacity for waste water flows and therefore at risk from flooding and spills to rivers. These increased flows mean that treatment and pumping costs will also increase and treatment processes become less effective.

The deterioration rate of sewers is closely linked to the degree and frequency of surcharge and therefore it is likely that rehabilitation costs will also rise.

The increased rainfall in winter will result in the river flood plains becoming more frequently inundated and backing up the sewers which outfall to them. Backflow through low level overflow structures may also occur more frequently.

A major consideration for the use of SUDS systems is their application and design for wet winter conditions when long rainfall events occur. The policy on drainage best practice, and in particular SUDS, takes account of the recommendations in this policy statement with regards to the likely increase in rainfall.

2.15.2 Drier Summers

Although the climate change model provides little information on short duration storms, it would seem that these events might become more intense when they occur. Unfortunately this will result in more polluted washoff after the extended dry periods and have a high impact on rivers which are likely to be running with lower flows and at increased temperatures. The potential for increased frequency of fish kills in rivers is therefore significant.

Although there is little evidence of summer events being much greater it is important to recognise the impact of a change in rainfall has on a drainage system. If there is an increase in rainfall intensity of 40 percent this will result in disproportionate flooding with analysis showing that flooding or storage provision can double.

An important aspect of drainage design is to minimise spill frequencies and pollutants that can pass to the receiving waters. The use of infiltration will help to maximise base flows in rivers.

- Wetter winters and much drier summers
- More infiltration into sewers in winter
- More polluted summer CSO spills, but probably fewer of them
- More CSO spills in winter
- Rivers more susceptible to pollution
- All these issues should be considered and allowed for if thought appropriate when designing drainage schemes

2.16 Groundwater

Groundwater changes are going to reflect the drier summers and wetter winters. However predictions are catchment specific and would therefore need to be derived from detailed analysis. The importance of groundwater changes for drainage policy is limited to the change in being able to use infiltration techniques and the exfiltration/infiltration of flows into structurally defective sewers.

The use of infiltration techniques (soakaways) is normally a function of soil type and antecedent rainfall conditions rather than groundwater level changes.

The infiltration and exfiltration into and from sewers through joints and cracks is primarily a function of the sewer structure. Again the flow rates involved are usually more a function of antecedent rainfall rather than the groundwater level.

3 DRAINAGE DESIGN CRITERIA

Drainage design criteria modifications to cater for Climate Change need to consider sea level rise, the use of joint probability of rainfall and sea level, and factors to be applied to rainfall events. River level and flow criteria are also relevant where procedures such as the Urban Pollution Management (UPM) are applied.

3.1 Rainfall Depth Factor – Design Events

Daily rainfall data for the Dublin area from the UKCIP02 model has been used to assess rainfall change. This amounts to the top 30 events in each year for both the present day (Control) model (30 years) and the future (2070 – 2100) model (30 years). This information includes the season in which they were predicted as taking place, but this has not been used in evaluating the change in return periods of extreme rainfall. An extreme value analysis has been carried out to determine the change in extreme rainfall. In addition, values obtained from the UKCIP02 report are provided where information is available. Recommendations have been made for future drainage design criteria and these factors should be applied to current design rainfall used for the Dublin region.

Although some analysis could be made with regard to the difference between summer and winter rainfall depths, current drainage design practice has yet to address and use these differences and only annual depths are used. As it is not possible to investigate rainfall event intensity profiles, it is proposed that the current summer and winter profiles continue to be used and that annual rainfall depths continue to be applied to either summer or winter events. Table 3.1 contains the rainfall depth factors determined from the extreme value analysis of the Dublin ’02 data. Table 3.2 provides supporting information from other sources which are also available to assist in decision making on criteria. All the values are based on Medium – High (A2) projections. The figures for Medium - Low (B2) are also available, but are generally significantly less. Based on the view that a precautionary position needs to be taken, only the Medium-High values are reported to avoid potential confusion.

Rainfall change (A2 scenario)	Daily rainfall return periods						
	2 yr	5 yr	10 yr	30 yr	50 yr	100 yr	200 yr
Rainfall depth ratio (factored on present day depths)	1.11	1.16	1.18	1.20	1.21	1.22	1.23
Rainfall return period ratio (as a function of present day daily rainfall return periods)	0.75	0.60	0.50	0.40	0.36	0.25	0.21

Table 3.1 The Dublin Region Daily Rainfall Depth Ratio Factors for 2080 (Medium - High)

The rainfall return period ratio in Table 3.1 is the result of assessing the effective reduction in return period of the present day depth of rainfall and seeing what the reduction in return period that represents for the future. Thus the 100 year event now is equivalent to a 25 year event in the future.

	Spring	Summer	Autumn	Winter	Annual
UKCIP02 2 year daily rainfall for Dublin region percentage change	+5 to +10	-10 to -15	+5 to +10	+20 to +25	+5 to +10
UKCIP02 Seasonal rainfall percentage change for the Dublin region	~ 0	-35 to -45	0 to -10	+15 to +20	0 to -10

Table 3.2 Other Climate Change Rainfall Data

Although there is no detailed research to draw on to show the change in rainfall characteristics for short high intensity events, there is a view that these are likely to be rather higher than the equivalent daily depth increases, but there is no evidence to this effect. This is based on the relationship between temperature and the energy generated in hot conditions. However as this is largely supposition, it is proposed that the daily values are used for all durations.

However this analysis is based on the single set of data for the Dublin “box” from the RCM3 model. Consideration of these results should be weighed against the known high level of uncertainty of rainfall prediction and the large variability between UKCIP98 and ’02 results and other climate models. In addition it is important to also take account of the impact of such a dramatic change this would make in terms of construction costs. Taking all these issued into account it is advised that all design rainfall events should be factored by 10 percent with the understanding that more detailed climate studies will be carried out for Ireland in the coming decade. This advice would then be updated against the findings of the research. This figure is supported by the study carried out by Maynooth on climate change (appendix C). The argument that this is not in keeping with the precautionary principle can be countered by the fact that rainfall change will be incremental and that it is not a matter of urgency to use design rainfall for the 2080s.

However it is important to be aware that the high degree of uncertainty also means that rainfall could significantly increase well above 10%. Emphasis should now be placed on designs which are assessed using sensitivity analysis and take account of risks/consequences of “failure” for a range of return periods. This therefore also leads to more emphasis on cost-benefit evaluation of schemes and the consequences of flooding.

- Design Rainfall profiles to be as currently used – England and Wales, Summer and Winter
- All present day design rainfall depths (hyetograph intensities) factored by 1.1
- Emphasis on sensitivity analysis and risk assessment on scheme evaluation
- Rehabilitation schemes only triggered by current levels of performance and not by predicted reduced levels of service

3.2 Rainfall Time Series

Time series rainfall is used to determine frequency and volumes of spills. The level of pollution of a spill to a river is a function of the antecedent dry period, the intensity of the storm and the flow in the river during the event. Key issues are therefore intensity and numbers of events. These should be considered on a seasonal basis (for both river states and bathing beaches) as well as taking into account seasonal differences in climate change.

Theoretically the TSR characteristics could change. For example in summer the events could be shorter, but more intense and fewer in total number. Unfortunately there is little information on this at present. UKCIP02 suggests that summers will be much drier and winters will be wetter. It also implies that the daily depths for the 2 year event are down 10% and up 20% for summer and winter respectively, but seasonally they are down 40% and up 20% respectively. On the basis of this limited information, Tables 3.3 and 3.4 have been produced to modify the current time series rainfall. The reason for applying a factor of 1.0 for the top 5 events for summer is due to the precautionary view that higher temperatures are likely to make summer thunderstorms more intense as it seems unlikely that increasing temperature across the country would result in less intense events for the large storms.

Time series (Summer: Apr – Sept)	
	Factor
Average event intensity	0.90
Top 5 events intensity	1.00
Number of events	0.60

Table 3.3 TSR Event Rainfall Factors for 2080-2100 due to Climate Change – Summer

Time series (Winter: October – March)	
	Factor
Average event intensity	1.10
Top 5 events intensity	1.10
Number of events	1.0

Table 3.4 TSR Event Rainfall Factors for 2080-2100 due to Climate Change – Winter

N.B. Factoring intensities of an event is the same as factoring the rainfall depth.

The practical implementation of this is to keep the top 5 summer events and drop out every other event between April to September. All winter events (October to March) would be the same. All events would have rainfall intensities factored by 0.9, 1.0 or 1.1 as stated in Table 3.3 and 3.4.

In practice these suggestions, although providing a method of allowing the present day time series to continue to be used to assess the future behaviour of the sewer system, is inadequate in providing a good representation of the future rainfall in the Dublin region. It is recommended that a stochastic series, based on the time series rainfall from the UKCIP02 results for the Dublin “Box” should be produced. Factors will still be needed to cater for the differences between North, East and South of the Dublin area.

As the antecedent dry weather period is important with regard to the use of time series rainfall for water quality and river pollution evaluation, it is suggested that all the antecedent dry weather periods for all summer events be increased by 3 days. This is very arbitrary, but this would be catered for more accurately in producing a stochastic time series rainfall generated from the ’02 data.

Time series rainfall factors applied to existing summer and winter time series for the Dublin region for 2080

- Summer: Average intensity - 0.9; except top 5 events – 1.0; Number of events – 0.6
- Winter: Average intensity – 1.10; Number of events – 1.0
- New stochastic time series rainfall for the Dublin region to be produced in the medium future

3.3 River Flow

River flow is relevant for a range of different reasons such as flora and fauna and supply resource. Drainage engineers also need to know the likely change in river state for the two reasons of flood levels and also summer low flows for dilution and pollution impact.

With the drier summers and wetter winters, the river response will also reflect this change in climate. The warmer summers will result in reduced soil moisture, and this together with the reduced rainfall volume will significantly modify the normal flow condition in rivers, particularly those with a limited groundwater source. Table 3.5 contains very tentative figures. No differentiation of factors between rare events and frequent events is suggested. It should be stressed that Table 3.5 is only for use for guidance to drainage engineers. Detailed assessment of climate change on rivers is recommended for river improvement studies and catchment strategy plans.

River	Q90 (low flow)	Q10 (high flow)
Flow rate	0.9 - 0.60	1.1 – 1.3

Table 3.5 River Flow Changes due to Climate Change

In addition to the flow regime of rivers being affected, it is likely that the water temperature may well be an issue of concern due to the implications of reduced dissolved oxygen and other stress factors affecting fish. Clearly there are other reasons for concern over falling river flows in summer, such as water resource issues, however as this policy statement is limited to drainage issues and also because the change in river characteristics has yet to be properly evaluated, no recommendations can be made in this regard.

Extreme caution should be applied to the use of these figures. River flow behaviour is a function of both the groundwater regime and rainfall runoff and therefore there will be a range of responses between rivers due to climate change.

- River flow regime changes due to climate change will vary significantly depending on their topographical and soil characteristics
- River base flows could reduce by as much as 40%
- River flood flows are likely to increase by around 20%
- Summer river water temperatures will be raised

3.4 Sea Level

Sea level rise is considered to be more certain in its prediction than precipitation change. The inertial effects of thermal warming make the immediate future look quite encouraging. However by the end of the 21st century the average sea level rise is projected by the UKCIP02 report to be around 300mm to 400mm around Ireland. However the thermal inertia means that even if CO_2 warming is controlled in the near future (which is not likely), sea level rise is projected to continue to rise by over one meter in the very long term. However there are some concerns in Ireland (Maynooth, 2003) that UKCIP02 does not give a conservative prediction. Their assessment of 8GCM models gives an average value of 480mm for the end of the century, with the difference mainly attributed to under prediction of easterly winds in the Hadley model. An additional feature, which must be considered, is the drop in land level relative to the ocean that has been measured as being 0.3mm per year for the Dublin region. Thus over 100 years this amounts to another 30mm. Thus taking a precautionary position it is suggested that a figure in the range of 400mm to 480mm is used.

It should be noted that Dublin has been and is likely to continue to be Ireland's premier city for centuries. Therefore it would seem appropriate to take a long term position on decision making with regard to areas which are likely to remain of high value, but might get threatened in due course by sea level rises beyond the next century. Thus although a cost benefit assessment rarely justifies the use of more than a 200 year level of protection, it is proposed that certain areas might be designed to take into account higher sea level rises. An example might be the Ringsend waste water treatment plant on the peninsula where the potential sea level rise of 1000mm in the long term might result in different strategic decisions being made; a move to diversify treatment. Also the implications of closing the works cannot be envisaged as a feasible option in the foreseeable future.

The results of the UKCIP02 study suggests that surge behaviour is not significantly different to what occurs currently and therefore the value of 400mm could be applied as a constant to all levels for different tidal return periods. However as there seems to be some debate as to the accuracy of the predictions for surge in the Irish sea, it might be appropriate to use a higher figure for higher return periods. To avoid further debate and recognise the accuracy limitations of predicting sea level rise, a figure of 400 - 480mm is proposed and is to be applied as a constant for all return periods, but should only be used to 1 decimal place.

The frequency of extreme tidal events has recently been revisited as part of the GDSDS project and is reported here for completeness to allow detailed recommendations to be made with regard to design levels. At present there appears to be some degree of uncertainty as to the current official advice on the design sea level for the 100 year and other return periods.

A statistical analysis of tidal recurrence was undertaken for annual maximum tides for the period 1923 to February 2002. Table 3.6 gives the level / frequency relationship for both an EV1 and EV2 analysis. The recent high tide in February 2002 of 2.95m is of particular concern, and this can be compared to the table of values. It can be seen that the event is either a 330 year event or 758 year event based on these data.

Criterion to protect against tidal flooding is often put at 200 years. As the EV2 analysis gives a value of 2.89m (close to the 2.95m of the recent tide) and because there is a degree of uncertainty in both the climate change model and the historical tidal data, it is recommended that 2.95m is taken as being the present day 200 year water level.

% Annual probability of occurrence	Return Period	Level m OD (Malin Head)	
		EV1	EV2
42.9%	**2.33**	2.30	2.31
20.0%	**5**	2.40	2.41
10.0%	**10**	2.48	2.50
4.0%	**25**	2.58	2.61
2.0%	**50**	2.66	2.70
1.0%	**100**	2.73	2.79
0.5%	**200**	2.81	2.89
0.2%	**500**	2.91	3.01
0.1%	**1000**	2.98	3.11

Table 3.6 Historical Analysis of Tide Levels for Dublin – Extreme Value Analysis

This analysis is theoretical and results for return periods greater than 100 years should be treated with caution. This is particularly true in this case as the highest tides have generally came from recent years, indicating that the "sample" is not representative for the whole period.

A final cautionary point needs to be made in that the figure 2.95m was recorded at the official recorder in Dublin (Alexandra Quay). However water levels were recorded as high as 3.1m at Stella Gardens and 3.35m in Newbridge Avenue even though river flows were not high. Care therefore needs to be taken in using tide level volumes.

The issue of freeboard is always considered in applying any design water levels and relates to the level of uncertainty or safety factor deemed appropriate. As the predicted measures of climate change are acknowledged as being quite uncertain, whether sea level or river levels, careful consideration of the appropriate level of freeboard needs to be taken. As this is often very site specific, and is not just a function of climate change, no quantitative guidance is made in regard to this issue.

- The future (2080-2100) 200 year tidal event shall be taken as 3.4m OD
- The increase in sea level will be taken as 440mm and applied to all present day extreme value maximum tidal return periods to one decimal place
- The present day extreme value sea levels will be taken as those shown in column EV2 in Table 3.6
- Strategic long term sea levels will be taken as 2.95m +1.0m or 4.0m OD (to 1 decimal place)
- The design sea levels refer to the Dublin Port gauge and higher levels will occur up river estuaries

3.5 Joint Sea Level, River Flow and Drainage System Analysis

The assessment of the level of service where high tides coincide with rainfall requires an understanding of the joint probability as discussed in chapter 2. However a clear understanding of the underlying statistics and appropriate methodology is not generally within the experience of many engineers and therefore a pragmatic and conservative set of assumptions needs to be applied to make sure that the coincidence of these events occurring is considered. In reality a range of various return periods of each variable (tide and rainfall) which, paired together have the same level of service, should be used. Consider the following example:

1 year tide, 50 year rain = return period 300 years (say)

50 year tide, 1 year rain = return period 300 years (say)

5 year tide, 5 year rain = return period 300 years (say)

All these combinations might provide the same level of probability, but the joint occurrence of the two 5 year events might provide the worst impact at the point of concern. Therefore if a simplistic set of rules are to be applied, the level of service must be set fairly conservatively to ensure that the system is not under designed.

However a further consideration needs to be made with regard to risk (probability and consequence). The consequences of tidal inundation are likely to be catastrophic while local flooding from a drainage system failure would have limited impact. Thus it would seem unreasonable to consider the same level of service being used for all joint probability scenarios. Added to this is the knowledge that extreme event prediction of both variables have their own levels of uncertainty and allowance needs to be built in for this element (whether for joint probability or simple one variable analysis). It is therefore suggested that the target return periods that should be exceeded for a range of combinations for applying a pragmatic joint probability analysis should be as follows:

Tidal inundation – 500 years

River flooding – 100 years

Drainage flooding – 30 years

In cases where there is a potential for life threatening situations to develop from rapid inundation due to breach of sea or river defences, then a standard of protection greater than the 1:200 year event should be considered. This may be as high as 1:500 or more depending on the level of risk involved.

It should be noted that the difference between the 1000 year tide and 100 year tide is only around 300mm. Therefore the apparent very conservative return periods suggested in fact do not represent very large differences between tide levels and rainfall amounts. The following return period selections are based on a conservative choice of correlation factors, which is discussed in appendix D.

River flooding evaluation (100 years):

- MHWS tide with 100 year river
- 1 year tide with 5 year river
- 5 year tide with 1 year river

Sewer system flooding evaluation, with tides (30 years):

- MHWS tide with 30 year drainage
- 1 year river with 1 year drainage
- 5 year tide with 0.25 year drainage

Sewer system flooding evaluation, with rivers (30 years):

- 0.25 river with 30 year drainage
- 1 year river with 5 year drainage
- 5 year river with 1 year drainage

4 RECOMMENDATIONS FOR INCORPORATING CLIMATE CHANGE ISSUES INTO DRAINAGE DESIGN CRITERIA

The accuracy of climate models is known to be limited, particularly with regard to issues related to drainage such as rainfall. However as nearly all measures of the various relevant parameters affecting drainage are believed to be negatively affected, it is important to take a precautionary stance on all drainage criteria. Climate change models will continue to improve and in due course these criteria will need to be revisited and revised as appropriate.

The following points summarise the recommendations on drainage criteria to be applied in the Dublin region made in this report.

1. The results of the Hadley Centre HADRCM3 model is to be used for climate change policy for the Dublin region

2. The UKCIP02 Medium – High (A2) SRES scenario should be used for climate change policy

3. The projections for 2080 should be applied to all infrastructure design unless design lives are considered to be short (30 years or less). Linear interpolation of the recommendations might then be applied.

4. Sea level rise for 2080 in the Greater Dublin area will be assumed as being 440mm.

5. The 200 year return period should be used for coastal flooding design and this level is 3.4m Malin AOD. Strategic long term Dublin area planning and highly sensitive areas (Ringsend WwTW) to use 4.0m AOD.

6. The design sea levels refer to the Dublin Port gauge and higher levels will occur up river estuaries.

7. A pragmatic approach to joint probability analysis for combinations of events can be taken initially, but more detailed joint probability analysis should be applied (see Appendix D) where costs are significant or other reasons require greater accuracy in assessing performance or flood risk. The following event combinations are proposed based on providing combined return periods greater than 100 years for river flooding affected areas and 30 years for sewerage systems affected by river or tidal levels.

   River flooding evaluation (100 years):

   - MHWS tide with 100 year river ;
   - 1 year tide with 5 year river;
   - 5 year tide with 1 year river.

   Sewer system flooding evaluation, with tides (30 years):

   - MHWS tide with 30 year drainage;
   - 1 year river with 1 year drainage;
   - 5 year tide with 0.25 year drainage.

   Sewer system flooding evaluation, with rivers (30 years):

   - 0.25 river with 30 year drainage;
   - 1 year river with 5 year drainage;

- 5 year river with 1 year drainage.

8. In cases where there is a potential for life threatening situations to develop from rapid inundation due to breach of sea or river defences, then a standard of protection greater than the 1:200 year event should be considered. This may be as high as 1:500 or more depending on the level of risk involved.

9. River flow changes in the future should be determined individually for catchment planning. However for the purposes of CSO drainage system performance evaluation, the following precautionary position should be taken.

    - River baseflows could reduce by as much as 40%.

    - River flood flows may increase by around 20%

10. Present day design rainfall depths are to be increased and factored by 10% (1.1)

11. New time series rainfall should be produced which represents future rainfall conditions.

    11.1 Present day time series rainfall are to be modified separately for summer and winter series:

    - Summer rainfall intensities to be factored by 0.9, except for the top 5 events

    - The number of summer rainfall events is to be reduced by 40%.

    - Winter rainfall intensities to be factored by 1.10

    11.2 A future stochastic rainfall time series should be produced in the medium term to properly reflect the projected change in seasonal rainfall pattern across the Dublin region. This might be based on time series RCM3 data for the area.

12. New drainage schemes should be evaluated using these recommended criteria but should also carry out risk and cost – benefit analyses. The consequence of "failure" should be a specifically influence scheme selection due to this uncertainty. However major rehabilitation or modification of the networks should still be based on evidence of need rather than the predicted reduction in level of service.

13. Explicit advice is not provided on issues relating to changes in infiltration, and other secondary effects that are likely to occur due to climate change. All these issues (discussed in chapter 2) should be considered and allowed for, if thought appropriate, when designing drainage schemes.

14. Ireland should decide whether to rely upon the UKCIP (or other modelling) work in the future, or carry out work on climate change modelling to support its policies dealing with future change.

15. Rivers and their quality are a very important issue for Ireland. The uncertainty with regard to river flows has far reaching implications for Ireland (water resources, fisheries, tourism) and although this document is focused on drainage issues, it is suggested that a climate change evaluation and policy is needed to address these issues.

16. The dependency element of joint probability analysis of tide, river and rainfall events should be evaluated to enable a better understanding of the level of service being provided. This is important as tide levels will have an increasing influence on drainage for large areas of the Dublin region.

5 IMPLICATIONS OF RECOMMENDATIONS

Although it is important to cater for the effects of climate change to ensure an adequate level of service is provided, the effects of these changes should be clearly understood in terms of both the impact on these changes on current system performance, but also the cost impact of solutions.

The following points are therefore worth noting:

1) These recommendations are based on the A2 (Medium – High) scenario, on the basis of taking a precautionary view of what may take place in the future. Selection of B2 (Medium - Low) scenario would significantly reduce the impact of these recommendations. What evidence there is, suggests current growth rates of $C0_2$ and other gases are currently closer to the higher scenario.

2) Where the existing level of service fails at 10 years, the projected increase in rainfall will now make it fail at 5 years. Similarly if a level of service is currently 50 years, the level of service now provided will drop to nearly 10 years. Generally the existing sewer system performance will appear to be significantly less competent than under the current rainfall characteristics.

3) Predicted flooding volumes from the network will increase by up to 50 percent compared to an analysis carried out with current rainfall characteristics.

4) Solutions to systems requiring storage will result in storage increasing by up to 50 percent with critical duration events becoming longer.

5) The return period level of protection of tidally affected areas will drop significantly. For example a 60 year tide will now have a 2 year level of protection and a 1000 year event will now drop to less than 50 years. This means solutions arrived at by pragmatic rules of thumb for joint probability should often be checked against the more accurate joint probability analysis where solutions are very costly.

6) The pragmatic approach to joint probability assessment provides conservative results in terms of the levels of protection. The levels of protection selected should vary based on the consequences of failure. Thus tidal failure resulting in massive inundation requires a higher level of service than failure from the drainage system.

7) The degree of certainty for various aspects of climate change varies depending on the parameter of interest. Sea level change is certain, but the rate of change is less clear. Nevertheless all relevant organisations are or should be taking appropriate precautionary action. The implications of applying the change in sea level criteria will be very significant in low-lying areas in terms of sea defences and, to a lesser extent, lowland drainage.

8) The degree of certainty with regard to hydrological change is acknowledged by all experts as being low. This is particularly true for extreme events that are critical for drainage design application. The implications of applying between 10 and 25 percent uplift on design rainfall will dramatically increase solution costs to deal with existing flooding and provision of storage. Costs would similarly rise by up to 50 percent compared to applying current rainfall criteria. Due to the level of uncertainty and the impact of changing design criteria to this extent, an interim proposal is suggested which is to use a global factor of 10% increase in rainfall depth until more scientific information becomes available. The uncertainty of the change in rainfall, together with the knowledge that these changes are predicted to take place over the coming century implies that proposed solutions needed to address system failures (failures to meet trigger criteria) should be approached in a flexible manner. Any solution on also existing networks should aim to meet target criteria based on current rainfall, but whether it satisfies future rainfall conditions, should be based on considerations of risk of “failure”.

Appendix A

Overview of the Climate Change Debate and the Scenarios for the Future

A1. INTRODUCTION

The global climate system is responding to increasing concentrations of greenhouse gases that have occurred since the start of the industrial revolution (~1750). Figure 2.1, in the main text, shows observed instrumental global-mean temperature anomalies for the period 1861-2000. Since 1860 (the beginning of reliable global temperature records), there has been a warming of nearly 0.7°C. It is also estimated that globally 1998 was the warmest year of the second Millennium (based on reconstructions from proxy climate sources, such as tree ring, ice cores, corals, and documentary evidence) and that the 1990s were the warmest decade.

A considerable amount of scientific research has been undertaken since the possibility of human-induced climate change was first openly discussed. The focal point for this research has been the United Nations Intergovernmental Panel on Climate Change (IPCC). The IPCC is charged with the task of reviewing the scientific literature and presenting its findings to international governments that have signed up to the UN Framework Convention on Climate Change (UNFCCC). Three reports have so far been produced in 1990, 1996 and 2001, with a further report planned for 2006.

Climate change has high public awareness, and within the EU it is widely accepted that there is now an artificial human-induced impact on the global climate system. The media, however, often incorrectly portray an impression of "balanced" scientific debate regarding the possible causes of the observed climate change. This is an inaccurate presentation of the situation, since the weight of scientific evidence as presented in the peer-reviewed literature supports the statement that there is a "discernible human-influence on the climate system" (IPCC, 1996), and that most of the observed warming during the 20th Century can be attributed to human activities (IPCC, 2001).

Dublin is a fast growing city, and is in a unique position, surrounded on the south and the west by upland regions, open country to the north and to the east by the Irish Sea. Changes in rainfall, which have been identified in the observational records, will affect runoff and, combined with increasing urbanisation of the rural component of the surrounding catchments, it is likely that flooding will be an increased problem. Sea-level rise will pose a problem to the low-lying regions of Dublin. When attempting to estimate the effects of the impacts of future climate change, there is also a need to take into account the changing socio-economic conditions that will effect the Dublin region during the 21st Century as well as the purely technical issues.

The aim of this Appendix is to present the current understanding of present and future climate states of relevance to the Dublin Bay region. Uncertainties in the science, and other possible causes of the observed climate change will also be addressed.

A2. THE CAUSES OF OBSERVED CLIMATE CHANGE

Whilst the balance of scientific evidence supports the view that there is a discernible human influence on the global climate system, and that this can be attributed to increasing concentrations of greenhouse gases, a number of contrasting viewpoints are often aired in the public environment. To understand the full causes of climate change there is a requirement to examine those factors that cause the climate to vary over all time scales.

A2.1 Solar Variability

Change in the amount of the Sun's energy arriving at the top of the Earth's atmosphere is considered to be a major cause of climate variability. On the longest time scales of Earth's geological history, variability in solar output is thought to play a role in the Earth's climate, influencing the succession of glacial and interglacial epochs. On shorter time scales, over 10 to 100 years, which are important to humankind, sun spot cycles of around 11 years influence certain climate parameters. However, the fluctuations are weak and tend to appear and disappear without reason.

The 11-year sunspot cycle itself varies in strength on time scale of 80 years and longer, and these longer-term fluctuations have also been linked to climatic change. In the early 1600s, the sunspot cycle almost disappeared and this phenomenon, the so-called Maunder Minimum, has been associated with the height of the Little Ice Age, when glaciers reached their most advanced positions in the last four thousand years.

It has also been claimed that the warming of the 20th century was largely due to trends in sunspot activity, for example, in the length of the sunspot cycle. The evidence, however, for these apparent correlations is not strong. Moreover, the trends were insufficient to generate the observed climate changes without some (yet to be identified) amplifying mechanism. The IPCC (2001) conclude that the combined change in radiative forcing of natural factors (solar and volcanic as described in Section 2.2) is estimated to have been negative over the past four decades and that to date mechanisms for solar effects on climate have not stood up to rigorous analysis or are based on sound theory.

A2.2 Geo-catastrophes

Two known causes of major climatic disturbance are the impact of a large extra-terrestrial body, and the eruption of a "super volcano". Paleo-environmental evidence indicates that both events have occurred on several occasions in the past (e.g. the identified impact crater on the Yucatan Peninsula 65 million years ago). On the scale of human history (10,000 years), such events are mercifully infrequent, but no doubt they will happen again.

Only certain types of volcanic eruption have an effect upon the climate. The eruption has to be of sufficient magnitude to emit very large quantities of dust and sulphate aerosol into the stratosphere (20-25km above the Earth's surface) and, for maximum impact, it should occur in lower latitudes. The most well known eruption of historical times was Tambora, Indonesia in1815. The following summer became known as "the year without a summer" in many parts of the Northern Hemisphere.

Mount Pinatubo which blew in 1991 fulfilled these conditions but was less severe, and in fact the ensuing veil of gases cooled the atmosphere by about 0.2-0.3°C for almost two years. The cooling effect after volcanic eruptions is most evident during the Northern-hemisphere summer months, because the veil slightly reduces the amount of sunlight that reaches the Earth's surface. The 1992 summer over the British Isles was the coolest for 25 years.

On a par with volcanic activity, a major extraterrestrial impact could also be cataclysmic. These operate in much the same way, by injecting a cloud of dust and gases into the upper atmosphere. However, these incidents appear to be even rarer than major volcanic eruptions.

A2.3 The Greenhouse Effect

Atmospheric gases like water vapour and carbon dioxide do not interfere to any great extent with incoming solar energy. Once that energy reaches the Earth's surface, it is absorbed, warms the land and ocean surface of the planet, and is then re-emitted. The amount of heat re-emitted and eventually lost to space must equal the amount gained from the Sun if the temperature of the planet is to remain constant. However, the so-called terrestrial energy stream is now different in character, since additional concentrations of greenhouse gases are interfering with the previous balance and now capturing more of the outgoing energy.

The greenhouse gases absorb outgoing terrestrial energy, trapping it near the Earth's surface, and causing further warming. This is the "greenhouse effect". Without this effect, the planet would be too cold to support life, as we know it. Unfortunately, humanity, through energy generation, changing land use and other processes, has produced a substantial increase in the concentration of greenhouse gases in the atmosphere, enhancing the natural greenhouse effect, and it is feared that this continued interference would lead to a major shift in global climate, i.e. humans are 'enhancing' the natural greenhouse effect.

Climate variability can also be generated by smaller-scale changes in the energy balance, being the balance between heat received and heat lost. Many processes can lead to the disruption of regional climate. Due to its enormous mass, and inertia, the ocean and its currents have a major effect even on distant regions, through effects on precipitation and wind patterns. The El Niño Southern Oscillation (ENSO) phenomenon, for example, has major climatic and societal implications, particularly in the tropics and much of North America. Effects of ENSO on Europe are negligible.

A3. THE CURRENT STATE OF CLIMATE SCIENCE

The climate system is complex and inherently chaotic, and in order to understand and appreciate its behaviour climatologists have constructed mathematical models. The current state-of-the-art models are three-dimensional mathematical representations of the coupled ocean-atmosphere-biosphere system, known as GCMs (General Circulation Models or Global Climate Models). These models are detailed and complex and require large super-computing capacity. As a result, there are only a limited number of centres around the world that can construct such models and perform experiments with them. One of these facilities is the Hadley Centre at the UK Met Office, as described further in Section 5 of this Appendix.

A4. UNCERTAINTIES IN THE SCIENCE

There are a number of uncertainties in the construction of climate change scenarios. The best way to examine the uncertainties in climate science is to view them in the context of a chain of processes, from socio-economic forcing factors through to impacts of climate change. Uncertainties are present at each stage, from the use of socio-economic projections to the resultant emissions scenarios and the climate model experiment. Additional uncertainties are incorporated if adaptation and mitigation strategies are considered.

The four key elements that give rise to uncertainties in any future projections of climate are:

A4.1 Socio-Economic Conditions

Future socio-economic forcing conditions (i.e. the production of greenhouse gases) are largely unquantifiable and cannot be assigned probabilities since, for example population growth and energy demand cannot be projected with confidence. This is one reason why future estimates of climate must be treated as scenarios. To allow for this uncertainty, a range of emissions, such as the SRES emissions scenarios (SRES, 2000), are generally used. However, the use of multiple emissions scenarios has not always been possible because of computing constraints. Many GCM experiments have been undertaken which examine the effects of just one emissions pathway.

A4.2 Climate System

The climate system is inherently chaotic and therefore, impossible to predict with any degree of accuracy in the long term because of the high frequency variability that exists. There are also uncertainties in several key parameters, for example the climate sensitivity to increasing concentrations of greenhouse gases, and the time lags between atmospheric and oceanic processes.

A4.3 Impact Assessments

The level of uncertainty in climate change impacts depends upon the activity sector, the complexity of the methodology used, and the region of interest. For example, for water resources the impacts of rising temperature on evapotranspiration may or may not outweigh the impacts (in a given region) that precipitation changes would have on water resources. In other sectors, social changes such as increasing population and/or increasing standards of living may dwarf any impact from the climate. For a given impacts sector, different 'impacts models' will produce different results even with the same climate input.

A4.4 High Impact Low Probability Events

Certain events due to their low probability of occurrence are by their nature unpredictable. One possible climate disruption that has been hypothesised is that a large amount of fresh water (produced by a rapid melting of Greenland's ice sheets) is input into the North Atlantic. There would then be a breakdown in the thermohaline circulation, tending to a disappearance or severe weakening of the Gulf Stream. In turn, this would cause a more continental (i.e. cold winters) climate over Northwest Europe. Whilst this hypothesis is plausible, and sudden switches in the Gulf Stream have occurred in the geological past, only very extreme scenarios of greenhouse gas emissions have generated such effects in the GCM, and only after many decades.

A5 INTRODUCTION TO GCM AND RCM MODELS

General Circulation or Global Climate Models are the best tools available for modelling the response of the climate system to changes, such as that brought about by changes in concentrations of greenhouse gases. GCMs are a development of numerical weather forecasting models. To date there are a limited number of centres around the world that have the resources to run sufficiently long integrations of GCMs. Current GCMs operate at a spatial resolution of approximately 3^{o} by 3^{o} degrees longitude and latitude. Even at this apparently coarse spatial resolution very large supercomputing resources are required.

The Hadley Centre at the UK Met. Office is recognised as one of the world's leading climate modelling centres, using two 900 processor Cray T3E supercomputers. Two versions of the Hadley Centre's coupled climate model, HadCM2 and HadCM3, have been more widely used in impacts assessments than any other. More recently in order to enhance the resolution of the output for Europe, the Hadley Centre has used their Regional Climate Model (HadRM3) to perform a series of high resolution (~50km) integrations. The HadRM3 model is driven by output from HadAM3, which is an atmosphere only GCM, with a resolution of 1.25^{o} by 1.765^{o}.

The outputs from climate change experiments have been widely used in impact assessments, which have been reviewed most comprehensively in the IPCC Reports, Climate Change 1995 and The Regional Impacts of Climate Change, 1997. However, there are a number of difficulties associated with using the GCM results for climate impact studies.

To use the results of GCM climate change experiments in a consistent manner, researchers therefore need to understand how GCMs work, what their limitations are, and how to adopt a suitable framework in which to adjust model results for regional or local conditions. This methodology is known as climate change scenario construction.

A6. FUTURE EMISSIONS OF GREENHOUSE GASES

In order to assess how the global (and subsequently the regional) climate system will respond in the near future, there is a need to estimate how future emissions of greenhouse gases will change. For the purposes of the GDSDS, the near future can be defined as the 21st Century.

The IPCC has produced the Special Report on Emissions Scenarios (SRES), which sets out the possible pathways for the evolution of global /regional population and future changes in socio-economic conditions. Four families of scenarios were classified:

A6.1 SRES A1

Scenario A1 (High) envisages a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources

(A1T), or a balance across all sources (A1B). Since 1990 this region has been following the AIFI scenario.

A6.2 SRES A2

Scenario A2 (Medium – High) envisages a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.

A6.3 SRES B1

Scenario B1 (Low) envisages a convergent world with rapid change in economic structures, "dematerialization" and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity.

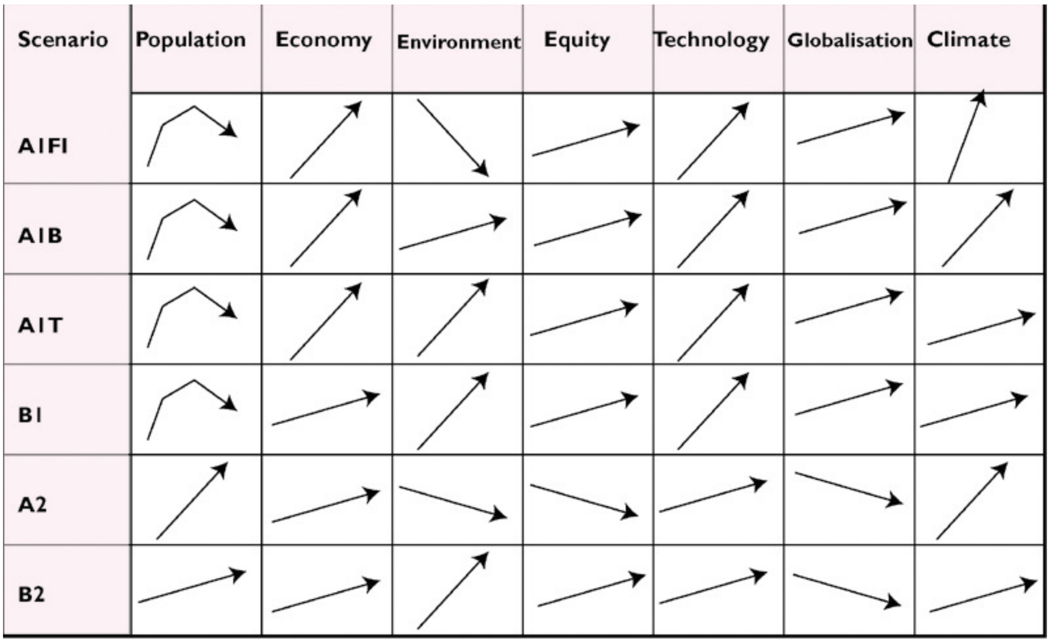
A6.4 SRES B2

Scenario B2 (Medium - Low) envisages a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local, rather than global solutions.

More complete details of these scenarios are provided in Appendix B.

A7. THE IMPACTS OF THE SRES SCENARIOS

Figure A1 shows the qualitative directions of the above SRES scenarios for a range of different indicators, which include population growth, equity and climate.



Scenario	Population	Economy	Environment	Equity	Technology	Globalisation	Climate
A1FI	↗↘	↗	↘	→	↗	→	↑
A1B	↗↘	↗	→	→	↗	→	↗
A1T	↗↘	↗	↗	→	↗	→	→
B1	↗↘	→	↗	→	↗	→	→
A2	↗	→	↘	↘	→	↘	↗
B2	→	→	↗	→	→	↘	→

Figure A1: The Qualitative Impacts of SRES Scenarios

This figure is designed to provide a guide as to the way different parts of the global environment and socio-economic systems are likely to change over the following century. The resultant climate change will be a factor of which SRES pathway we take as a society and the sensitivity of the climate system. The scenarios are, by definition, all equally plausible and it is therefore not recommended to treat one individual family as a "best guess" or "central estimate". By using a range of climate models, both simple and complex it is possible to estimate changes in emissions of greenhouse gases over the 21st century, as shown in Figure A2. The resultant future concentrations of these gases and their impacts upon global and regional climate are shown in Figure A3.

The climate sensitivity is defined as the equilibrium response of the climate to an instantaneous doubling of carbon dioxide, often quantitatively described as being in the range of 1.5°C to 4.5°C.

If we, therefore, follow a high impacts SRES scenario such as A1FI and a high climate sensitivity, the resultant global temperature change will be at the high-end of the projections. The opposite is true if we follow a low impacts SRES scenario such as B2 and combine that with a low climate sensitivity.

The SRES emissions scenarios are set from a 1990 baseline, and we are therefore 12 years down a given pathway, which is most akin to the A1FI scenario.

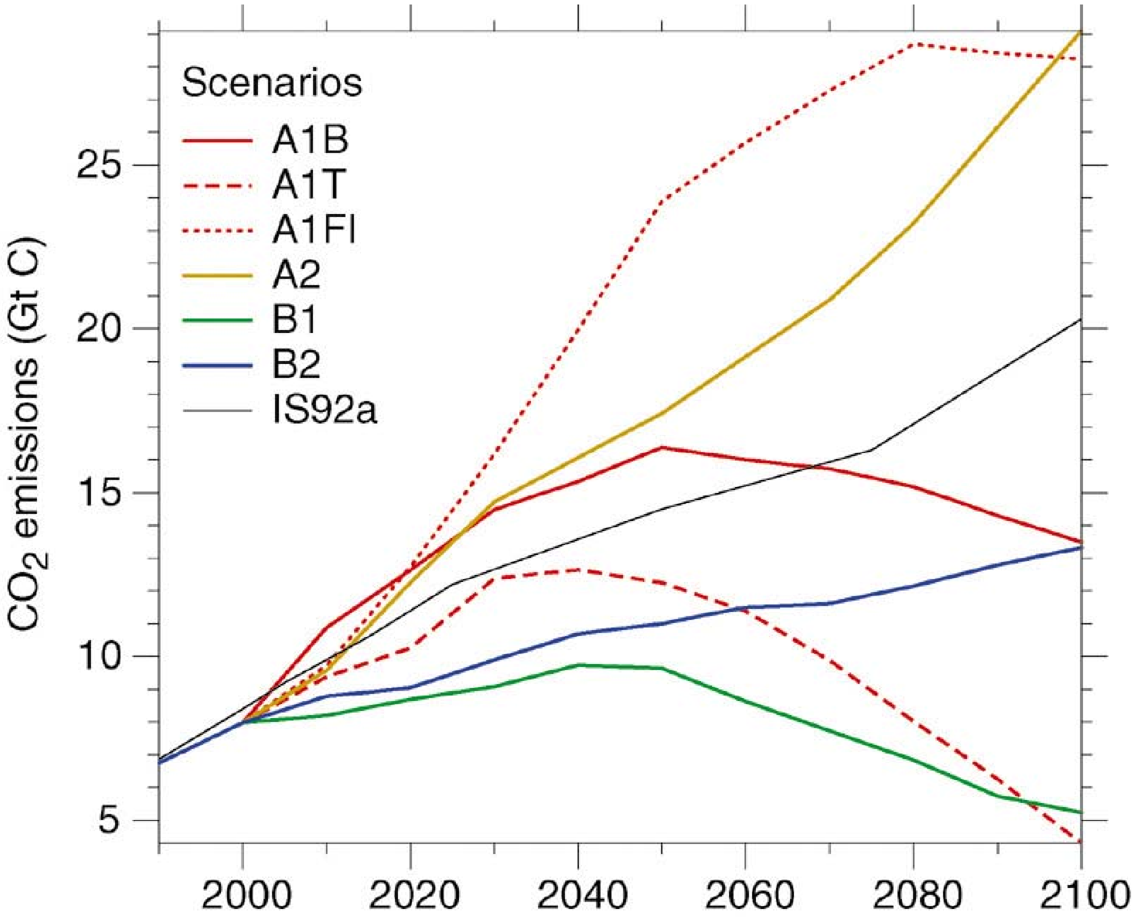


Figure A2: Projected CO_2 Emissions for SRES Scenarios

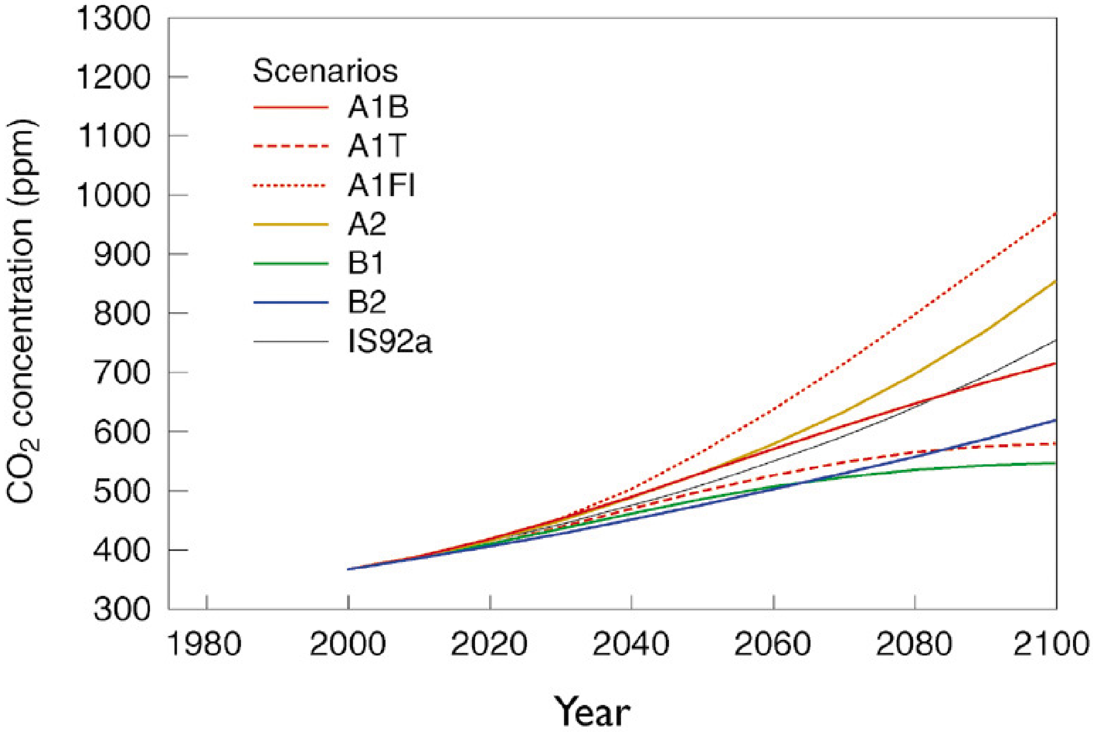


Figure A3: Projected Atmospheric CO_2 Concentrations for SRES Scenarios

A7.1 The Response of the GDSDS to the SRES Scenarios

The Greater Dublin Area (GDA) will evolve not only in response to climate changes but also socio-economic changes. The GDA that will evolve in response to the A1 pathway will be very different to that of the GDA of the B2 world. Socio-economic changes, therefore, are likely to have an important impact upon the future growth in the GDA as well as those from climate change.

For example, if the global system follows the A1 pathway the GDA will experience rapid population growth for the next few decades (possibly up to the middle of the century), and per capita income will increase. Increased economic growth will increase pressures for higher value domestic properties, personal transport requirements; "out of town" retail outlets and increase the pressures for more intensive commercial properties. Overall there will be an increase in population density and increasing demand for resources.

On the contrary B2 pathway, the GDA's population will grow at a slower rate, and per capita income will increase more slowly than present. With lower economic growth there will be lower demand for high value domestic properties and personal transport requirements. There will be an enhancement of local communities and there will be less demand for intensive commercial properties. The GDA developed area may increase but there will be overall a lower population density and lower demand for resources.

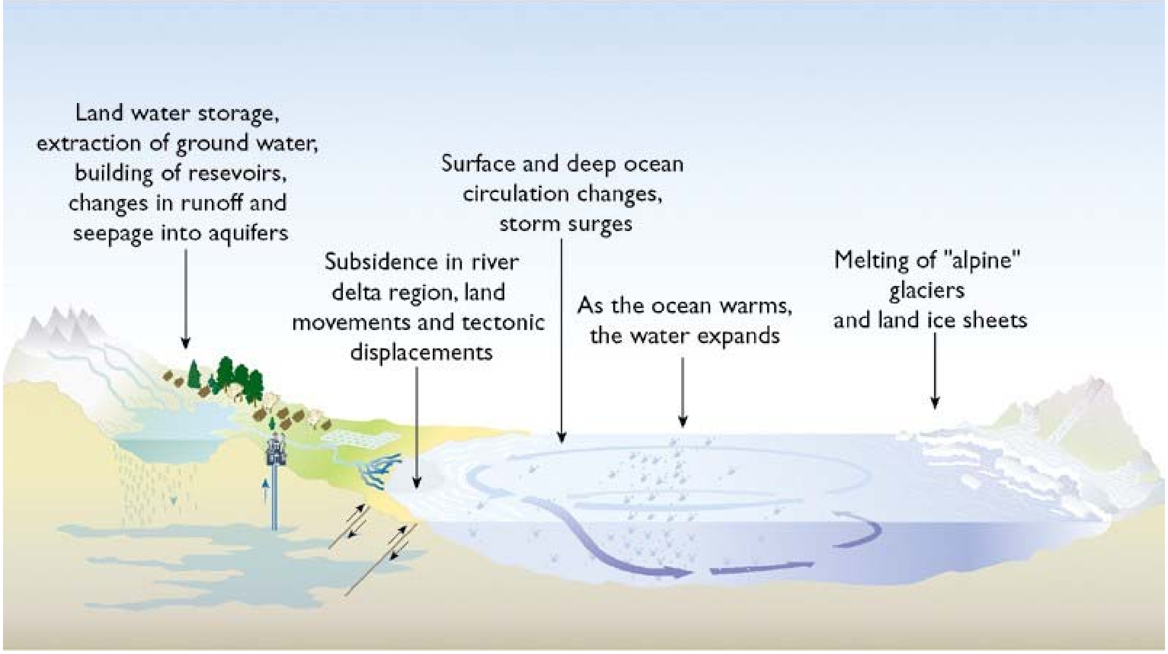


Figure A4: The Causes of Sea Level Rise

A8. CHANGES IN SEA-LEVEL

Sea level rises and their impacts for the GDA are determined by a range of factors, operating over a range of time scales. These time scales can be measured in hours in the case of tides, up to millions of years, when estimating the effects of ocean basin and tectonic changes. Such causes of sea level rise are illustrated in Figure A4.

Changes in sea-level rise are an important impact of rising temperatures. Sea level will rise through a number of contributing factors, the most important being the thermal expansion of the water as a result of increasing temperatures and the melting of alpine glaciers around the world. The main uncertainty is associated with the contribution of ice sheets. Greenland is likely to loose mass through melting, however this contribution to increasing sea level may be offset by the predicted growth in the Antarctic ice-sheet. However uncertainty arises from our insufficient knowledge of the stability of some of the large ice sheets, most notably the West Antarctic Ice-Sheet (WAIS). A collapse of WAIS could lead to sea level rise in excess of 3 meters within a few decades.

In certain regions tectonic movements will exaggerate sea-level rise. Parts of the British Isles are largely affected by the isostatic rebound that has existed since the end of the last ice age. Parts of the south and east are sinking relative to the present sea level. It is estimated that the Dublin Bay region is sinking at a rate of approximately 0.3 mm/yr.

A8.1 Storm Surges in the Irish Sea

Whilst the gradual increase in sea-level will be a threat over long time periods to low lying land, a possible more immediate threat may arise from individual storm surges as demonstrated in February 2002. Whilst we can ascertain the likelihood of the rate of future sea-level rise, there are large uncertainties associated with modelling storm surges. Storm surges are a result of a combination of factors, including tidal height, depth of depression and wind direction. Whilst we can predict tidal heights for the foreseeable future there is greater uncertainty associated with estimates of future changes in wind speed, direction and severity of Atlantic depression systems. The UKCIP 2002 scenarios show only slight changes in wind speed over the coming century, and therefore the model predicts that we are not likely to see changes in storm surge frequency or magnitude that are different to current day conditions. Storm surge prediction is an area that is particularly uncertain with regard to the climate change model.

Work undertaken by the Hadley Centre and Proudman Oceanographic Laboratory and reported in the UKCIP 2002 Report (UKCIP, 2002) has driven a high resolution (30km) shelf-seas model with output from HadRM3.

Figure A5 shows the results for this modelling based on a scenario, which is approximate to the SRES A2 scenario. The Figure shows the spatial change in the height, in meters, of the 50-year return period sea level change, including surge, for the 2080's. The modelling takes into account the combined effect of global average sea-level rise and UK land movements, and indicates that the GDA is likely to experience an increase of around 30cm for the 50 year return event, towards the end of the 21st century.

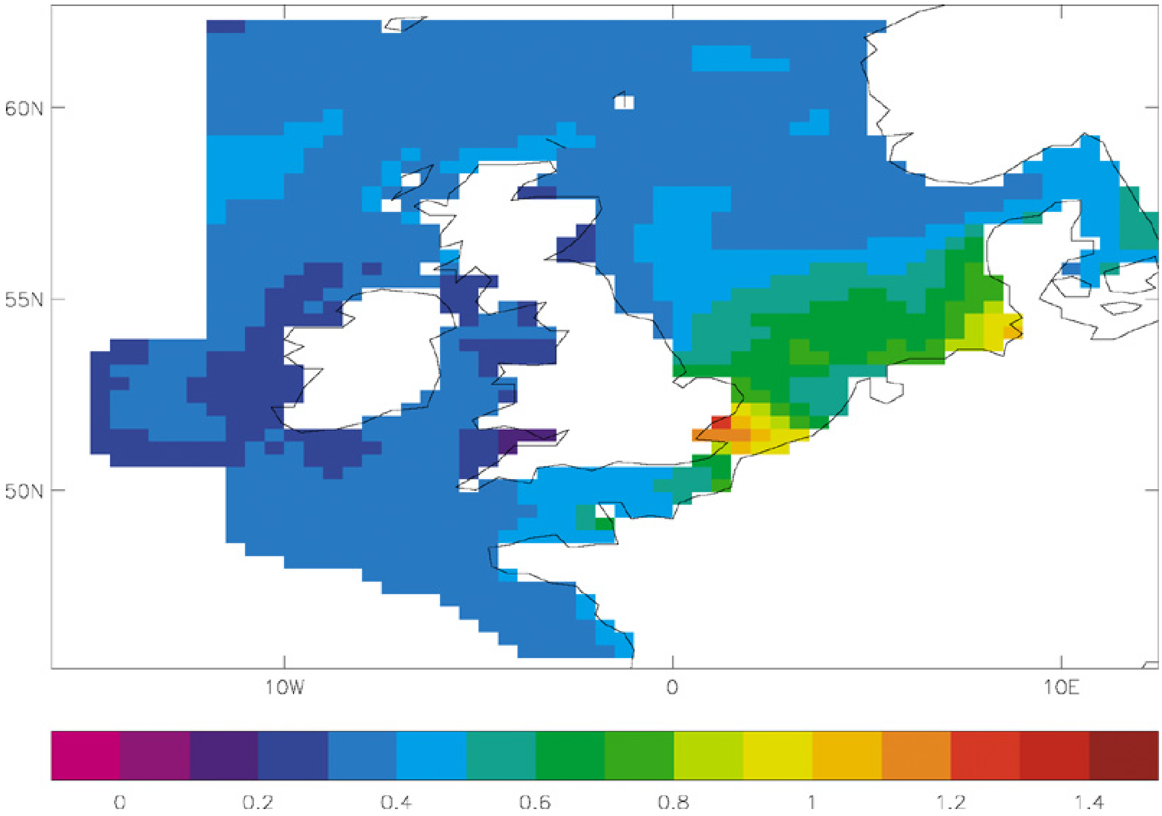


Figure A5: Change in Sea Level for the 50 year Event (2080s, Medium - High)

A9. PRECIPITATION CHANGES FOR THE DUBLIN BAY REGION

To undertake an analysis of changes in precipitation for the Dublin Bay region the results from a number of integrations performed with the HadRM3 model were analysed. These analyses equated to the current (1961-90) climate and the future (2070-99) climate, as defined by the SRES A2 and B2 emissions scenarios.

A9.1 Seasonal Precipitation Totals

HadRM3 A2a and B2a results generally predict wetter conditions over Ireland for winter and drier conditions for summer. Figure A6 shows the seasonal changes for the A2 and B2 scenarios as a percentage increase of rainfall over the period 1960-1990.

These results shows that increases in winter precipitation of between 15 and 25% can be seen over the Dublin region for the A2 run, and around 5% for the B2 scenario. Increases are higher to the east over the Irish Sea and smaller over central and eastern Ireland. A strong decrease in precipitation in summer is shown, with decreases of between 35% and 45% over the Dublin region for both the A2 and B2 scenarios. Decreases of greater than 45% in southern Ireland are strongest in the A2 run. Precipitation changes in the other seasons are generally negligible, except for the autumn results for the A2 run, which show a decrease in precipitation of between 5% and 15% over eastern Ireland. Annual changes are dominated by the strong winter decrease, and show a general decline of between 5% and 15% over most of Ireland.

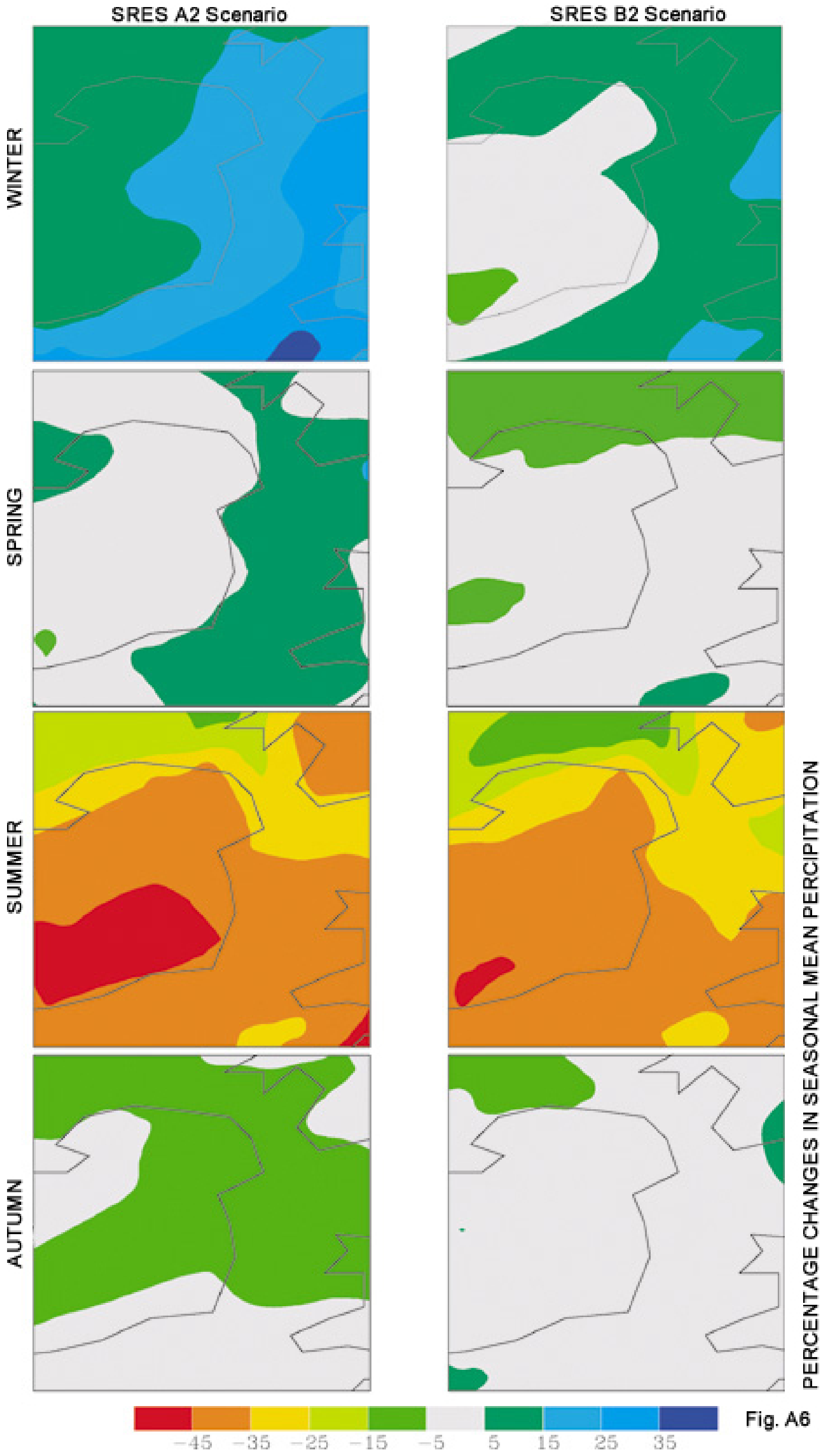


Figure A6: Percentage Changes in Seasonal Mean Precipitation

A9.2 Daily Rainfall Frequencies

Previous studies of expected changes in daily rainfall frequencies from greenhouse-related climate forcing have generally shown a decrease in the number of days with low rainfall and an increase in days with high rainfall over much of the globe (e.g. Gordon et al., 1993). Thus rainfall amounts change little but are falling in larger amounts on fewer days. A similar result can be seen in the HadRM3 results for the single grid point closest to the GDA, at location 53.35°N, 6.48°W.

Figures A7 to A10 show the frequency histograms for daily rainfall for the HadRM3A2 and HadRM3B2 simulations compared to current conditions. In all seasons there is a decrease in events with rainfall between 1mm and 5mm for both A2 and B2 scenarios, when compared to the 1961-1990 results. The decrease is strongest in summer, as shown on Figure A9.

The changes in the frequencies of higher intensity rainfall events reflect the seasonal mean changes in precipitation as mentioned earlier. In winter there is a small increase, in summer a strong decrease; and mixed results for the other seasons and annual results.

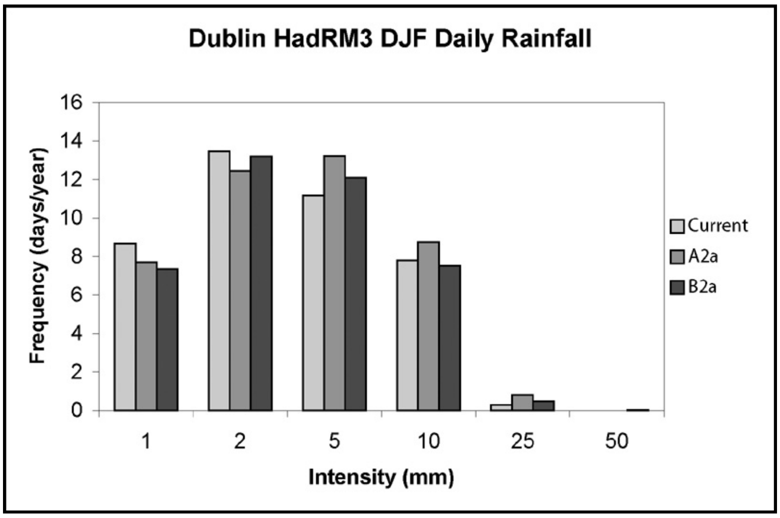


Figure A7 Daily Rainfall Frequency in Winter

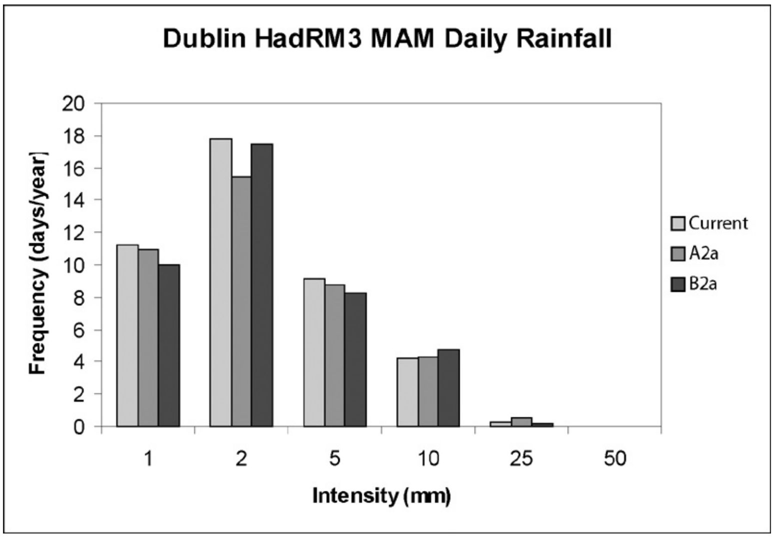


Figure A8 Daily Rainfall Frequency in Spring

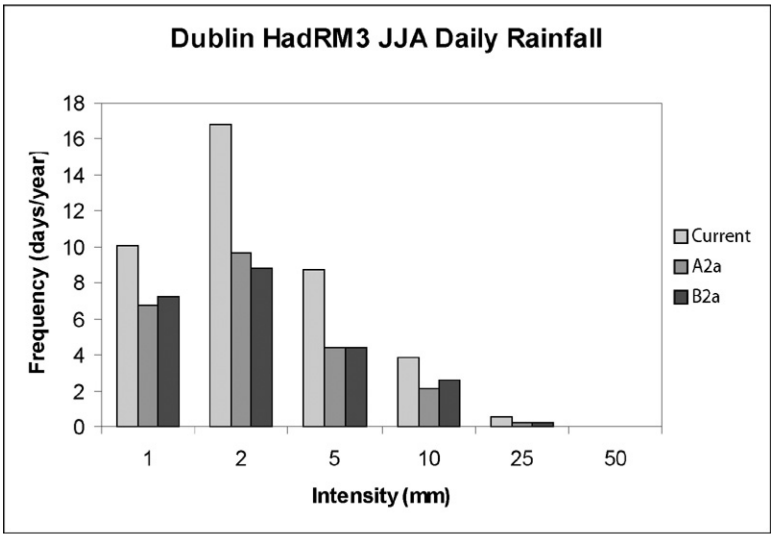


Figure A9 Daily Rainfall Frequency in Summer

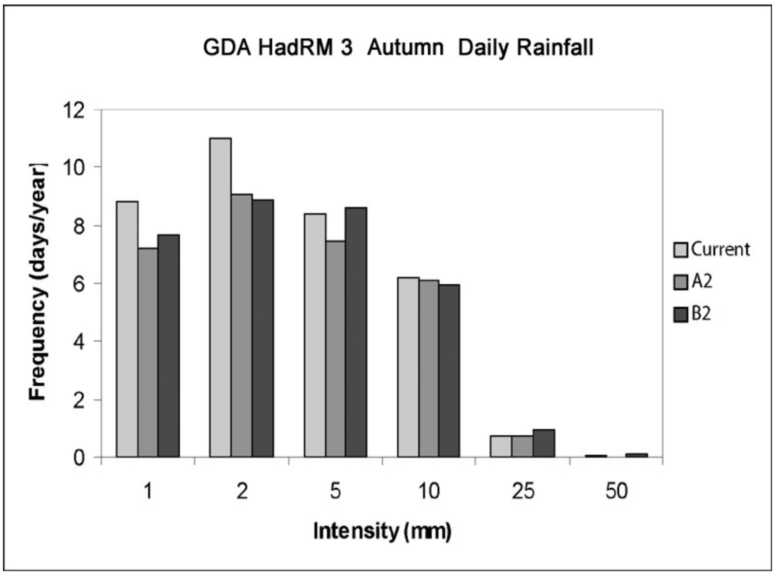


Figure A10 Daily Rainfall Frequency in Autumn

A9.3 Wet and Dry Spell Lengths

The time series of lengths of mean wet and dry spells are shown in Figure A11. A wet or dry spell is defined as a continuous run of days with rainfall above or below 1mm. The four panels illustrate the combination of wet and dry spells for future scenarios A2 and B2. The left-hand graphs in each panel show the mean seasonal and annual spell lengths for the current (1961-90) period, and the right-hand graphs show the corresponding spells for the future period.

In the time series for the wet spell lengths for the A2 scenario, the clustering of the seasonal series around the same mean for 1961-1990 suggests that there is little variation in wet spell length from season to season. For future conditions, the largest change is a drop in the length in summer, consistent with the observed reduction in rainfall for this season and reduced frequency in all rainfall categories. However, there is little difference in mean spell length between the seasons.

The dry spell lengths for the A2 scenario shows a similar clustering of the mean spell lengths around the same mean. The change in future conditions suggests that there is a marked increase in mean length in summer and a decrease in winter. This results in a greater spread of the mean values for each season. The inter-annual variability also increases in summer. The B2 scenario shows similar changes to the A2 scenario. There is little change in the wet spell lengths but dry spell lengths increase in summer and decrease in winter.

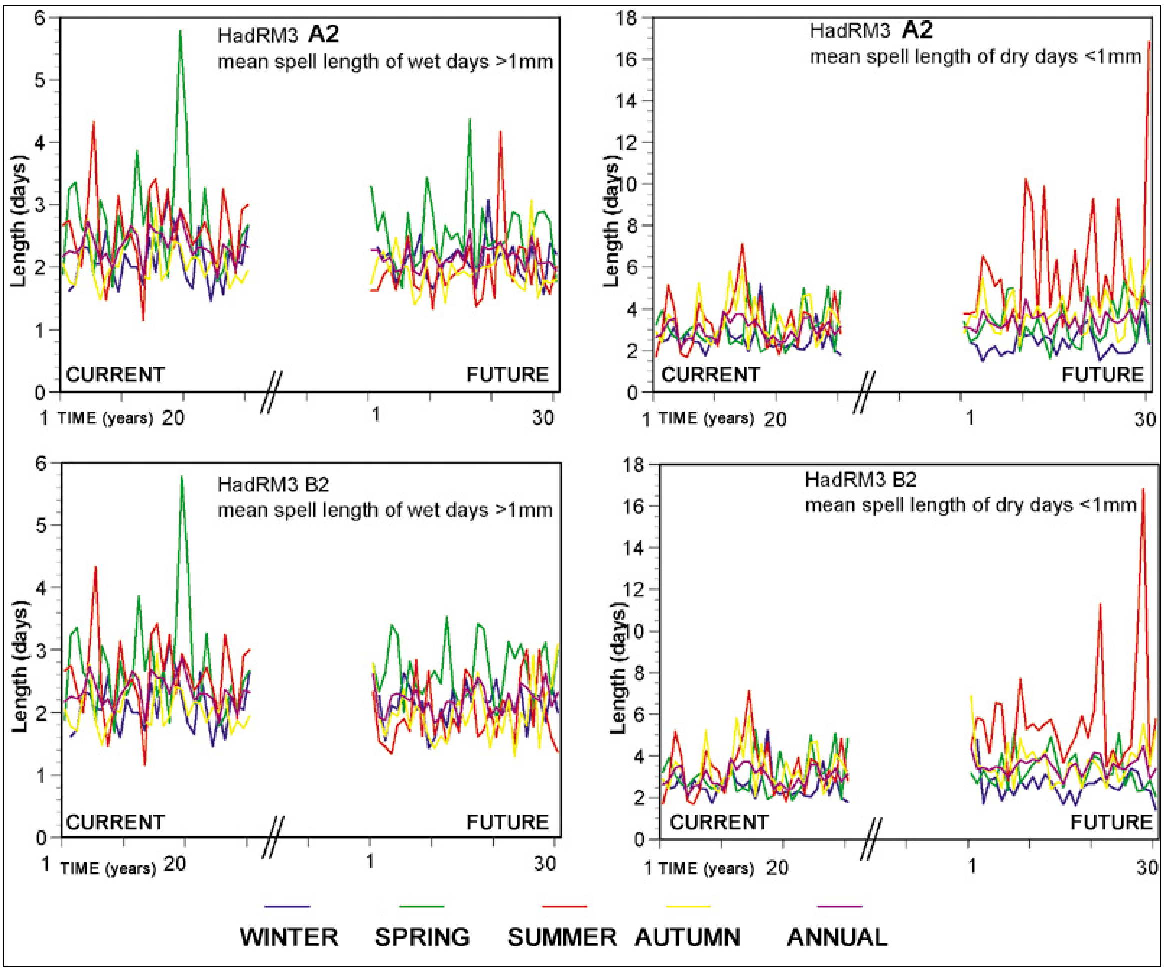


Figure A11 Lengths of Dry and Wet Spells for A2 and B2 Scenarios

A10. CLIMATE CHANGE PREDICTIONS FOR THE GDA

The likely physical effects of climate change, in particular sea level rise and changes in precipitation, are of particular interest to the drainage engineer. Ranges of predicted values are presented here corresponding to four climate futures for the British Isles. These climate change predictions have been based upon expert judgement and available evidence from the current climate science and climate change scenarios presented in this and other recent reports (e.g. UKCIP 2002, and Agnew and Viner, 2000).

These four predictions are descriptive examples of how the climate of the GDA is likely to evolve in the future and the resulting physical effects, based upon different levels of probability. Figure A12 shows the relationship between probability of the prediction occurring and the resulting rate of change in climate and physical parameters. Climate Change Prediction 1 represents what is likely to happen, whereas Climate Change Prediction 4 is a plausible scenario, based upon high values of climate sensitivity and rapid growth in greenhouse gas emissions, but with low probability of occurrence. Each prediction shows changes in mean temperature, precipitation, windstorms and sea-level rise.

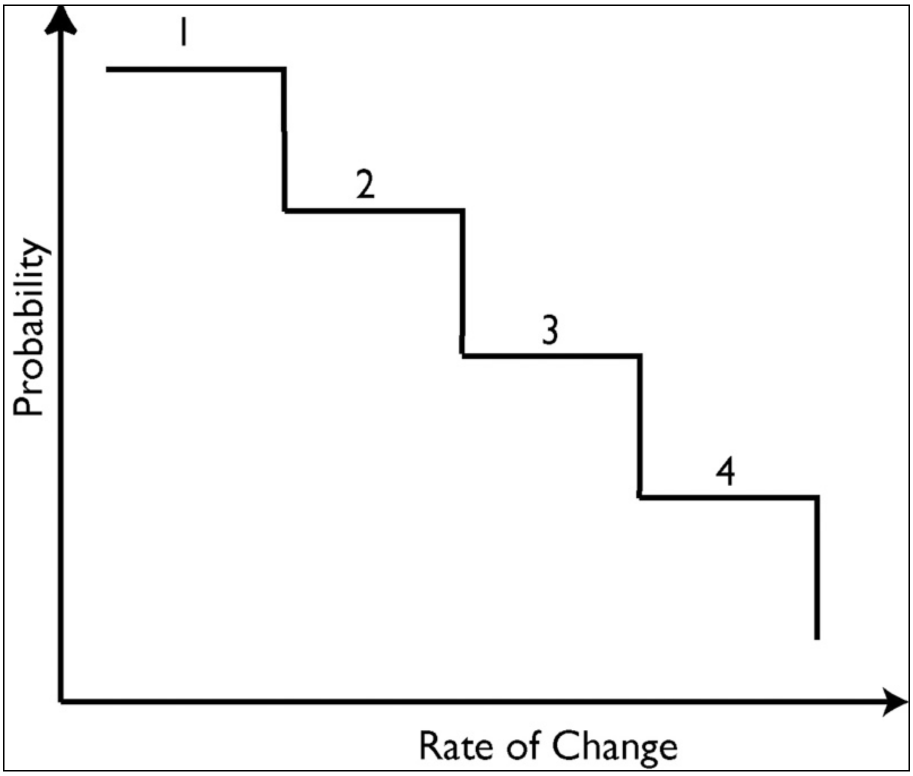


Figure A12: Probability of Climate Change Predictions

A10. 1 Climate Change Prediction 1 – High Probability

Mean temperature

0.2 to 0.3°C rise in mean temperature per decade

2020s 1.3°C Warmer; 2050s 2.0°C Warmer

Higher night-time temperatures; occasional cold winters

Precipitation

2020s Winters 7% Wetter; Summers 2% drier

2050s Winters 11% Wetter; Summers 15% drier

Higher number of intense winter rainfall events

Years with summer rainfall below 50% of 1961-90 average is approximately 1 in 5

Windstorms

No change in variability/frequency of extreme high impact (e.g. windstorms) events

Sea-level Rise

3 to 10cm increase per decade

2020s - 10cm increase; 2050s - 20cm increase

Localised coastal flooding due to higher tides - within design of sea-defences

A10.2 Climate Change Prediction 2 – Medium High Probability

Mean temperature

0.2 to 0.3°C rise in mean temperature per decade

2020s 1.3°C Warmer; 2050s 2.0°C Warmer

No repetition of early 1980 winters: Higher summer temperatures, higher nighttime warming

Precipitation

2020s Winters 10% Wetter; Summers 4% drier

2050s Winters 15% Wetter; Summers 17% drier

Higher number of intense winter rainfall events: Increase in winter fluvial flood events

Increase in summer droughts to 2 years in 3

Windstorms

No change in variability/frequency of extreme high impact (e.g. windstorms) events

Sea-level Rise

6 to 10cm increase per decade

2020s - 15cm increase; 2050s - 35cm increase

Severe localised coastal flooding, localised sea defence failures

A10.3 Climate Change Prediction 3 – Medium Low Probability

Mean temperature

0.3 to 0.4°C rise in mean temperature per decade

2020s 1.4°C Warmer: 2050s 2.4°C Warmer

No repetition of early 1980 winters; Higher summer temperatures, higher night-time warming

Higher number of extremely hot (+40°C) days

Precipitation

2020s Winters 12% Wetter; Summers 10% drier

2050s Winters 20% Wetter; Summers 20% drier

Higher number of intense winter rainfall events; Large Increase in winter fluvial flood events

Summer drought increase to 8 in 10 years

Windstorms

7% increase in severe winter and summer wind storms per decade

Increase in strong convective activity and associated features e.g. tornadoes

Sea-level Rise

10cm+ increase per decade

2020s - 25cm increase; 2050s - 60cm increase

Increase risk of 1953-style event; Increase in number of Towyn style storm-surge events

Localised permanent coastal inundation

A10.4 Climate Change Prediction 4 – Low Probability

Mean temperature

0.4 to 0.5°C rise in mean temperature per decade

2020s 1.8°C Warmer; 2050s 3.0°C Warmer

Increasing number of very hot days; No cold winters

Precipitation

2020s Winters 15% Wetter; Summers 15% drier

2050s Winters 20% Wetter; Summers 20% drier

Higher number of intense winter rainfall events: Regular number of winter fluvial flood events

Summer drought increase to 9 in 10 years

Windstorms

15% increase in severe winter and summer wind storms per decade

Common strong convective activity, and associated features e.g. tornadoes

Sea-level Rise

10 - 30cm increase per decade (WAIS Collapse)

2020s - 37cm increase: 2050s - 100cm increase

Permanent coast land loss, outside the range of sea-defences

A10.5 Application of Climate Change Predictions

Climate Predictions 1 and 2 have been constructed to capture the ranges of change for a number of variables as described by the IPCC. For example the 4 to10cm rise of sea level per decade and the temperatures changes are prescribed by a climate sensitivity of 1.5 to 4.5°C. The predictions are time dependent, but where possible show estimates of rates of change rather than changes expected by a given period. One problem that exists in presenting climate change predictions for given periods in the future (e.g. the 2050s) is that many stakeholders see this as a distant time horizon, which is beyond their envelope of experience.

The probability-dependant predictions presented here are designed to be used as guides in risk assessment studies, for assessing possible future impacts, and identifying thresholds that may exist within a given exposure unit, e.g. transport, insurance, agriculture and water resources. Therefore if a given sector or exposure unit, in this case the GDA, is vulnerable to the effects of Climate Prediction 1, it shows that the GDA has a high degree of sensitivity to climate change, and greater consideration must be given to adaptive and mitigation actions. In contrast, if it is perceived that GDA is not sensitive to Climate Change Prediction 4, then there is less sensitivity to future climate change.

Appendix B

The SRES Scenarios

B1 THE A1 FAMILY OF SCENARIOS

The A1 Family world is a case of rapid and successful economic development, in which regional averages of income per capita converge. Current distinctions between poor and rich countries eventually dissolve.

In this scenario family, demographic and economic trends are closely linked, as affluence is correlated with long life and small families (low mortality and low fertility). Global population grows to some nine billion by 2050 and declines to about seven billion by 2100. Average age increases, with the needs of retired people met mainly through their accumulated savings in private pension systems.

The global economy expands at an average annual rate of about three percent to 2100. This is approximately the same as average global growth since 1850, although the conditions that lead to a global economy in productivity and per capita incomes that are unparalleled in history. Income per capita reaches about €21,000 by 2050. While the high average level of income per capita contributes to a great improvement in the overall health and social conditions of the majority of people, this world is not without its problems. In particular, many communities could face some of the problems of social exclusion encountered by the wealthiest countries in the 20th century and in many places income growth could come with increased pressure on the global commons.

Energy and mineral resources are abundant in this scenario family because of rapid technical progress, which both reduce the resources need to produce a given level of output and increases the economically recoverable reserves. Final energy intensity (energy use per unit of GDP) decreases at an average annual rate of 1.3 percent.

With the rapid increase in income, dietary patterns shift initially significantly towards increased consumption of meat and dairy products, but may decrease subsequently with increasing emphasis on health of an ageing society. High incomes also translate into high car ownership, sprawling sub-urbanisation and dense transport networks, nationally and internationally. Land prices increase faster than income per capita. These factors along with high wages result in a considerable intensification of agriculture.

Three scenario groups are considered in the A1 scenario family, reflecting the uncertainty in development of energy sources and conversion technologies in this rapidly changing world. Near-term investment decisions may introduce long-term irreversibility into the market, with lock-in to one technological configuration or another. The A1B scenario group is based on a balanced mix of energy sources and has an intermediate level of CO_2 emissions, but depending on the energy sources developed, emissions in the variants cover a very wide range. In the fossil-fuel intensive scenario group A1FI, emissions approach those of the A2 scenarios; conversely in scenario group A1T with low labour productivity or of rapid progress in "post-fossil" energy technologies, emissions are intermediate between those of B1 and B2.

These scenario variants have been introduced into the A1 world because of its "high growth with high tech" nature, where differences in alternative technology developments translate into large differences in future greenhouse gas emission levels Ecological resilience is assumed to be high in this world. Environmental amenities are viewed in a utilitarian way, based on their influence on the formal economy. The concept of environmental quality might change in this world from "conservation" of nature to active "management" - and marketing - of natural and environmental services.

B2 THE A2 SCENARIO

For the A2 emissions scenario the main emphasis is on a strengthening of regional and local culture, with a "return to family values" in many regions. The A2 world "consolidates" into a series of roughly continental economic regions, emphasising local cultural roots. In some regions, increased religious participation leads many to reject a materialist path and to focus attention on contributing to the local community. Elsewhere, the trend is towards increased investment in education and science, and growth in economic productivity. Social and political structures diversify, with some regions moving towards stronger welfare systems and reduced income inequality, while others move towards "lean" government. Environmental concerns are relatively weak, although some attention is paid to bringing local pollution under control and maintaining local environmental amenities.

The A2 world sees more international tensions and less co-operation than in A1 or B1. People, ideas and capital are less mobile so that technology diffuses slowly. International disparities in productivity, and hence income per capita, are maintained or increased. With the emphasis on family and community life, fertility rates decline only slowly, although they vary among regions. Hence, this scenario family has high population growth (to 15 billion by 2100) with comparatively low incomes per capita relative to the A1 and B1 worlds, at €7,200 in 2050 and €16,000 in 2100.

Technological change is rapid in some regions and slow in others as industry adjusts to local resource endowments, culture, and education levels. Regions with abundant energy and mineral resources evolve more resource intensive economies, while those poor in resources place very high priority on minimising import dependence through technological innovation to improve resource efficiency and make use of substitute inputs. The fuel mix in different regions is determined primarily by resource availability. Divisions among regions persist in terms of their mix of technologies, with high-income but resource-poor regions shifting toward advanced post fossil technologies (renewable sources in regions of large land availability, nuclear sources in densely populated, resource poor regions) and low-income resource-rich regions generally relying on older fossil technologies.

With substantial food requirements, agricultural productivity is one of the main focus areas for innovation and Research and Development efforts in this future. Initially high levels of soil erosion and water pollution are eventually eased through the local development of more sustainable high-yield agriculture.

Although attention is given to potential local and regional environmental damage, it is not uniform across regions. For example, sulphur and particulate emissions are reduced in Asia due to impacts on human health and agricultural production, but increase in Africa as a result of the intensified exploitation of coal and other mineral resources. The A2 world sees high energy and carbon intensity, and correspondingly high greenhouse gas emissions. Its CO_2 emissions are the highest of all four scenario families.

B3 THE B1 SCENARIO

The central elements of the B1 future are a high level of environmental and social consciousness combined with a globally coherent approach to sustainable development.

A strong welfare net prevents social exclusion on the basis of poverty. However, counter-currents may develop and in some places people may not conform to the main social and environmental intentions of the mainstream in this scenario family.

Particular effort is devoted to increasing resource efficiency. Comprehensive incentive systems, combined with advances in international institutions, permit the rapid diffusion of cleaner technology. Research and Development to this end is also enhanced together with education and capacity building for clean and equitable development. Organisational measures are adopted to reduce material wastage, maximising reuse and recycling. The combination of technical and organisational change yields high levels of material and energy saving as well as reductions in pollution. Labour productivity also improves as a by-product of these efforts. Variants considered within the B1 family of scenarios include different rates of GDP growth and dematerialisation (e.g., energy intensity declines).

The demographic transition to low mortality and fertility occurs at the same rate as in A1 but for slightly different reasons, motivated partly by social and environmental concerns. Global population reaches nine billion by 2050 and declines to about seven billion by 2100. This is a world with high levels of economic activity and significant and deliberate progress toward international and national income equality. Global income per capita in 2050 averages €13,000, somewhat lower than in A1. A higher proportion of this income is spent on services rather than on material goods, and on quality rather than quantity, because of less emphasis on material goods and also higher resource prices.

The B1 world sees a relatively smooth transition to alternative energy systems as conventional oil resources decline. There is extensive use of conventional and unconventional gas as the cleanest fossil resource during the transition, but the major push is towards post fossil technologies driven in large part by environmental concerns.

Given the high environmental consciousness and institutional effectiveness in the B1 world, environmental quality is high, as most potentially negative environmental aspects of rapid development are anticipated and dealt with effectively locally, nationally, and internationally. For example, transboundary air pollution (acid rain) is basically eliminated in the long-term. Land-use is carefully managed to counteract the impacts of activities potentially damaging to the environment. Cities are compact and designed for public and non-motorised transport, with suburban developments tightly controlled. Strong incentives for low-input, low-impact agriculture along with maintenance of large areas of wilderness contribute to high food prices with much lower levels of meat consumption than those in A1. These proactive local and regional environmental measures and policies also lead to relatively low greenhouse gas emissions even in the absence of explicit interventions directed at mitigating climate change.

B4 THE B2 SCENARIO

Like B1, the B2 world is one of increased concern for environmental and social sustainability, but the character of this world differs substantially.

Education and welfare programs are widely pursued leading to reductions in mortality and, to a lesser extent, fertility. The population reaches about 10 billion people by 2100, consistent with both the United Nations and IIASA median projections. Income per capita grows at an intermediary rate to reach about €12,000 by 2050. By 2100 the global economy might expand to reach some €250 trillion. International income differences decrease, although not as rapidly as in scenarios of higher global convergence (A1, B1). Local inequity is reduced considerably through the development of stronger community support networks.

Generally high educational levels promote both development and environmental protection. Indeed, environmental protection is one of the few remaining truly international priorities. However, strategies to address global environmental challenges are less successful than in B1, as governments have difficulty designing and implementing agreements that combine environmental protection with mutual economic benefits.

The B2 world presents a particularly favourable climate for community initiative and social innovation, especially in view of high educational levels. Technological frontiers are pushed less than in A1 and B1 and innovations are also regionally more heterogeneous. Globally, investment in Research and Development continues its current declining trend, and mechanisms for international diffusion of technology and know-how remain weaker than in scenarios A1 and B1, but higher than in scenario A2. Some regions with rapid economic development and limited natural resources place particular emphasis on technology development and bilateral co-operation. Technical change is therefore uneven. The energy intensity of GDP declines at about one percent per year, in line with the average historical experience of the last two centuries.

Land-use management becomes better integrated at the local level in the B2 world. Urban and transport infrastructure is a particular focus of community innovation, contributing to a low level of car dependence and less urban sprawl. An emphasis on food self-reliance contributes to a shift in dietary patterns towards local products, with reduced meat consumption in countries with high population densities.

Energy systems differ from region to region, depending on the availability of natural resources. The need to use energy and other resources more efficiently spurs the development of less carbon-intensive technology in some regions. Environment policy co-operation at the regional level leads to success in the management of some trans-boundary environmental problems, such as acidification due to SO2, especially to sustain regional self-reliance in agricultural production. Regional co-operation also results in lower emissions of NOx and VOCs, reducing the incidence of elevated tropospheric ozone levels. Although globally the energy system remains predominantly hydrocarbon-based to 2100, there is a gradual transition away from the current share of fossil resources in world energy supply, with a corresponding reduction in carbon intensity.

Appendix C

Climate Change in Ireland

C.1 WORLD-WIDE MANAGEMENT OF CLIMATE CHANGE

In recognition of the acknowledged linkage between greenhouse gases and climate change and the worldwide nature of its effects, management of climate change has concentrated on control of emission of greenhouse gases.

In common with all other European Union Member States, Ireland signed the Kyoto Protocol on 29 April 1998. The Protocol will enter into force when sufficient parties have ratified it, including developed countries, accounting for at least 55% of the total emissions from this industrialised group. Ireland and the EU ratified the protocol in May 2002. Its entry into force is contingent on more countries ratifying the protocol as the threshold of 55% has yet to be achieved.

The Kyoto Protocol targeted the EU with achieving overall reduction in emissions of greenhouse gases, compared with emissions in selected base years. The reduction of 8% is measured on the whole basket of gases and lesser reductions achieved with some gases can be compensated by greater reductions in other gases.

Greenhouse Gas	Base Year	Percentage Reduction
Carbon Dioxide (CO2)	1990	8%
Methane (CH4)	1990	8%
Nitrous Oxide (N2O)	1990	8%
Hydrofluorocarbons (HFCs)	1995	8%
Perfluorocarbons (PFCs)	1995	8%
Sulphur Hexaflouride (SF6)	1995	8%

Table C1: Reduction Targets for Greenhouse Gases

The Protocol requires that these reductions in emissions be achieved by 2008 to 2012, with demonstrable progress in their achievement by 2015.

C.2 IRELAND'S INVOLVEMENT IN EU REDUCTION OF GREENHOUSE GAS EMISSIONS

In recognition of their varied circumstances, the EU agreed differing targets for individual Member States. For Ireland the target is to limit the net growth of emissions to 13% above 1990 levels. The main greenhouse gas in Ireland is carbon dioxide, mainly arising from the burning of fossil fuel in transport, heating and electricity generation.

Ireland's compliance with the Kyoto Protocol is managed by the Department of the Environment, under its National Climate Change Strategy (NCCS). The NCCS identified the main Sectors in Irish society responsible for emission of greenhouse gases, and set down targets for each sector to reduce annual emissions of carbon dioxide equivalent by 2008 to 2012. The NCCS was published in October 2000, with the latest report on progress being issued in May 2002.

C.3 TARGETS TO BE ACHIEVED

Irish emissions of greenhouse gases in the base year of 1990 were equivalent to 53.752 million tonnes (Mt) of carbon dioxide. In the period 2008 to 2012, Ireland's Kyoto commitment is to limit the net growth to 13% above this 1990 level, being emissions equivalent to 60.7 Mt of carbon dioxide.

Without the measures set out in the NCCS, Irish emissions were projected to reach 37% above 1990 base levels, being 73.8 Mt, by 2010. The NCCS therefore needs to reduce these projected emissions by a minimum of 13 Mt of carbon dioxide equivalent to meet the specified 13% rise. Full implementation of the NCCS aims to reduce emissions by over 15 Mt of carbon dioxide equivalent during 2008 to 2012.

C.4 PROGRESS ON ACHIEVING TARGETS

The NCCS Progress Report of May 2002 contains details of progress on schemes within the various Sectors.

Sector	Target Reduction set in 2000	Reductions / potential reductions of measures underway in 2001
Energy Supply	5.65 Mt	1.86+ Mt
Transport	2.67 Mt	1.38 Mt
Built Environment and Residential	0.90 Mt	0.30 Mt
Industrial, Commercial & Services	2.0 Mt	-
Agriculture	2.41 Mt	-
Forestry Sinks	0.76 Mt	0.04 Mt
Local Authority Waste	0.85 Mt	-
Local Authority Landfill	0.8 Mt	-
Total for All Sectors	16.04 Mt	3.58 Mt

Table C2 Annual Reductions in CO_2 Equivalent Emissions

During the latter half of 2002, the first review of the NCCS will be undertaken to monitor performance of the reduction schemes and to assess whether additional action is required to meet targets.

C.5 IMPACT OF CLIMATE CHANGE

The EPA supported research programme, carried out by the National University of Ireland, Maynooth, has developed climatic scenarios for Ireland for the periods 2041 to 2070 and 2061 to 2090. Their predictions include:

General increase in January temperatures of approximately 1.5 degrees Celsius by 2050, will rise to approximately 2.5 degrees Celsius by 2075. The effect will be less in the Dublin region with overall winter temperature increases of approximately 1.5^0 C;

Summer temperatures will increase by approximately 2^0 C by 2050, rising further by 2075. Increases in the Dublin region will be more pronounced, predicted to be 3^0 C;

Winter rainfall will increase by an average of 11%, although little change is predicted for the East Coast, and the Dublin region;

Marked reductions in summer rainfall across eastern and central Ireland, of the order of 25%;

Magnitude and frequency of individual flood events will probably increase in the western half of the country;

Agriculture in eastern parts will be affected by drought;

Sea-level changes will affect the south of the country first, especially low-lying coastal regions. The effects of sea-level rise will be most apparent in Cork, Limerick, Galway and Dublin.

The project also examined potential indicators of the occurrence of climate change in Ireland. Changes in primary indicators, such as temperature and rainfall, and secondary indicators, such as bird migration, concluded that the Irish climate is already changing, mirroring trends at a global scale, but a few years behind.

Appendix D

Joint Probability Analysis – Tides and Rainfall

D.1 INTRODUCTION TO THE USE OF JOINT PROBABILITY ANALYSIS

Dublin, like many cities on the coast, is having to consider the impacts of climate change of which sea level rise is, in the long run, likely to cause the greatest problem. As sea levels rise, the frequency of very high tides threatening the city with flooding will become more frequent and engineers will need to be able to evaluate risk of flooding to determine appropriate solutions to protect the Dublin area. This section is provided to give some guidance on the approach that needs to be taken to enable the necessary calculations to be carried out if a more detailed approach is warranted due to cost or project complexity.

Assessment of flood risk is rarely simple, often involving several interacting environmental variables (e.g. sea level, rainfall, waves, river levels) with unknown distributions and several interacting structural responses (e.g. flood propagation, drainage) which can only be estimated. The probability of coastal flooding, on any particular defence length, usually depends on the simultaneous occurrence of large wave heights and a high sea level. The probability of downstream river flooding may depend on the simultaneous occurrence of high river flow and a high sea level. The probability of heavy loading of a drainage system during intense rainfall, coupled with the system's inability to discharge storm water due to tide-locking, will depend on the simultaneous occurrence of high short-duration rainfall and a high sea level.

This section addresses just one of the potential problems, namely the extent to which occurrences of high values of the separate environmental variables are correlated with each other, and how that information might be used in drainage system design. This does not allow a three variable assessment of return period for river, tide and rainfall, though this calculation can be made where it is deemed necessary. This section has been specifically written for tide levels, but river levels are equally relevant for drainage outfalls to rivers.

The assumption of full dependence between relevant environmental variables will always be conservative - often over-conservative to a degree that cannot be quantified by the designer. Consider the response of a drainage system to a scenario consisting of the simultaneous occurrence of a 100 year return period sea level and a 100 year return period short-duration rainfall. Under the assumption of full dependence, this scenario would occur once, on average, every 100 years, and the drainage system might be designed to cope under this scenario. However, for truly *simultaneous* occurrence, both variables would need to peak in roughly the same 3-hour period of time (the top of the tide cycle).

The opposite approach would be to assume complete independence between the relevant environmental variables. This is potentially unsafe, and could lead to a significant under-estimate of potential flood risk. The calculations are slightly more complicated than those for full dependence, and independence should not be assumed without careful justification. Continuing the scenario of the previous paragraph, as there are nearly 300,000 3-hour periods in 100 years, in the unlikely case of the variables actually being independent, that exact scenario would occur only once, on average, in about 30,000,000 years! As an aside, it is a common error to combine, say, a 2 year return period sea level with a 50 year rainfall and assume that the combined return period (assuming independence) will be 100 years, but this represents only the probability that the two high values will occur during the same year.

Correct estimation of dependence can be as important in assessing overall risk as correct estimation of the two individual variables. Designers may choose to assume full dependence between relevant environmental variables, but it would nevertheless be useful to have some understanding of the degree of conservatism implicit in that assumption.

One might expect some dependence between the relevant environmental variables since these variables are driven to some extent by recent meteorological conditions. It would be easy for design purposes to assume that all relevant environmental variables take their maximum values simultaneously, i.e. to assume full dependence between them, and this is a common approach, particularly where rivers are short and partly urbanised and therefore respond in much the same way as drainage systems. However, in the case of sea levels, meteorological dependence tends to be muted by the effect of astronomical tide, which is unrelated to weather conditions – high waves or high rainfall may not occur on the highest astronomical tides and may not even persist over high water. Also, different variables may respond at different rates to severe weather conditions, introducing a time lag between occurrences of peak values of different variables, or they may be driven by different types of severe weather conditions.

Assessment of dependence is not a trivial task, as it varies between different locations and between different variable-pairs, and without analysis of locally measured data, it is difficult to provide guidance on the appropriate dependence value to use. However typical values can be provided for guidance and a recommendation is made in the absence of this information.

D.2 JOINT PROBABILITY ANALYSIS METHODS

Joint probability analysis puts together information on high and extreme values of each of two (or more) variables, with information on the dependence between one (or more) key variable-pairs, to derive high and extreme values of the joint distribution. The derived information is then used as input to flood risk calculations where the risk is dependent on the joint probability of the variables concerned.

Preliminary calculations and/or general experience will give an indication of the key variables involved and whether a joint probability analysis may be helpful. Both river flow and sea level may be important for river defence calculations, but sea level may have little influence upstream and river flow may have little influence downstream. Where tide-locking of drainage systems can occur, a joint probability assessment of high sea level and high rainfall will usually give some insight into the probability of occurrence.

There is a range of methods available for assessment of dependence and joint probability, depending on the quality and duration of the source data available and the accuracy required.

Ideally, the approach would involve simultaneous measurements of each of the relevant environmental variables, recorded close to the site of interest. However this note presumes this approach is not possible and provides an alternative desk approach with assumptions on dependency. This desk study approach is based on pre-computed combinations of two variables, expressed in terms of their marginal (single variable) return periods, for a small number of idealised dependence relationships. Although this does not have the precision and flexibility of an analytical approach, it is very much quicker to apply, and offers a significant advantage compared to an arbitrary approach such as assuming full dependence or independence, particularly where solutions result in expensive proposals.

The following section provides enough detail on this approach for it to be applied in situations where an estimate of dependence between two key variables can be made. The example assumes that the two key variables are sea level (i.e. tide plus surge) and short-duration rainfall. However, the method can also be applied to any variable-pairs.

D.3 DESK STUDY METHOD FOR JOINT PROBABILITY ANALYSIS

It is assumed that we know the frequency characteristics for both sea level and rainfall, for return periods between about 0.1 and 100 years. It is assumed that we wish to determine combinations of high sea level and high rainfall with a joint exceedence return period in the range of about 5 to 200 years. If one makes an assumption about dependence, then the return period for any combination of events can be determined.

The desk study method provides a means of combining the two separate sets of extreme values, expressed in terms of their marginal (single variable) return periods, for different levels of dependence and for different joint exceedence return periods. There will be more than one such combination for any given joint exceedence return period, and in any particular calculation, it is necessary to test all such combinations in order to find the worst case for a particular location. These combined conditions are called joint exceedence extremes, and the associated joint exceedence return period refers to the average time between occasions when both variables simultaneously exceed their specified values.

It is assumed that conditions at each successive high water (about 707 per year) are independent of those occurring at the previous high water and that each one is a potential 'event'. Dependence is conveniently expressed in terms of a 'correlation factor' representing the number of times more likely it is that an extreme rainfall will occur simultaneously with an extreme sea level, than would be expected under the assumption of independence. To estimate an event with a joint exceedence return period of 100 years, assuming independence, we might combine a 100 year rainfall with just a median high water level. However, with a ' moderate correlation factor' of 10 or 50, for example, we would combine the 100 year rainfall with a sea level exceeded only 10% or 2% of the time, respectively.

D3.1 Step 1: Extreme Sea Level

Obtain values of present-day extreme sea levels, covering the range in which tide-locking could occur. Allow for climate change adjustment and increase levels by the appropriate amount. Interpolation between specified marginal return periods can be achieved by plotting sea level against the log of return periods.

D3.2 Step 2: Rainfall / Drainage or River Flow Impact

Similarly the rainfall or river flow return periods of a range of design events are defined. Note that the critical duration storm will be affected by tide locking effect and this duration is likely to change with return period of both rainfall and tide level.

D3.3 Step 3: Assign a Level of Dependence

Until a body of case studies has assessed the level of dependence in the Dublin area, there is little information on which to base an estimate of dependence, but the tables below cover the wide range of possibilities found in several UK studies. The four example levels of dependence are called 'none', 'modestly correlated', 'well correlated' and 'strongly correlated', and until there is evidence to the contrary it would be prudent to assume 'well correlated' for rivers, although the most typical level of dependence for tides would be 'modestly correlated'.

It should be noted that dependency is a function of the joint return period. Therefore values vary for every combination of individual tide and rainfall.

The derivation of the joint return period is defined as follows:

Joint RP = RP(T) . RP(R) . 1/CF . 707 [eq. 1]

Where:

RP(T) is the return period of the Tide level

RP(R) is the return period of the rainfall or river event

CF is the Correlation Function or level of dependency

707 is the number of tides in the year

It should be noted that this is effectively an iterative process as CF is a function of the Joint RP. It is difficult to solve the equation by using values of specific return periods of tide and rainfall to then determine the Joint return period of such an event.

Typical values of dependency for a joint RP of 100 years are;

- none = 2
- modestly correlated = 20

- well correlated = 100
- strongly correlated = 500

In providing these figures, it is recognised that these figures will become enshrined as the values to be used rather than as indicative values. However it is important to make engineers aware of the scale of the values and therefore they have been provided for information.

The value of 2 might seem unexpected for “none”. The explanation for this is not obvious, but is a function of the fact that tides have a distribution and not a single level. A layman’s view of the Correlation Function is to think that if there is strong correlation between high tides and high rainfall, then there is 500 times more chance of having a high tide coinciding with an extreme rainfall than in a situation where the events are totally independent.

In the case of the combination of Drainage and River flows the number of events are less well defined, but there are generally acknowledged to be around 100 events a year. Of course rivers and sewer systems both respond as a result of rainfall and therefore there is clearly a high level of correlation between the occurrence of a high river flow and high sewer flow. However the critical duration of each system is usually very different (except where there is extensive storage in the drainage system) and also river flood characteristics are also a function of antecedent weather conditions. Thus an analysis of rivers and sewers should not assume the critical duration of each system occurs at the same time and run the return period of interest, but run the same duration event on both the river and sewer system. However this is a simplistic approach of dealing with the small degree of non-dependence between these two variables. A value of “strongly correlated” (equivalent to the value of 500 for the tidal assessment) and another of “very strong correlation” can be derived for this joint probability issue for the 100 events a year (reflecting the number of rainfall events). These values are:

- strongly correlated = 170
- very strongly correlated = 400

The values selected for the degree of correlation for the tidal analysis is based upon experience of studies that have had the data to do the necessary evaluation. The Correlation Function values for the 100 year event for river and sewer joint return period analysis is not based on any previous joint correlation analysis and therefore must be treated as such.

D3.4 Step 4: Determine Values for Level of Dependence (CF)

As stated earlier, the value of CF is a function of the Joint return period. This is defined as follows:

$CFrp = [Antilog \{ [log (CF_{100} /2) . log (707 . JRP/2)] / log (70700 /2) \}] . 2$ [eq. 2]

where CFrp is the Correlation Function for a joint return period

CF_{100} is the Correlation Function for the 100 year return period

JRP is the Joint Return period of interest

Then if CF_{100} is chosen and JRP is known, CFrp can be determined.

Similarly for the drainage and river combination the formula for equation 2 would be modified to:

$CFrp = [Antilog \{ [log (CF_{100} /2) . log (100 . JRP/2)] / log (10,000 /2) \}] . 2$ [eq. 3]

D3.5 Step 5: Joint Probability Tables

Having determined CFrp for a specific Joint return period, equation 1 is then used trying a range of different combinations of Rainfall and Tides which all satisfy the Joint Return Period target value, one can determine the impact of these joint events. It should be stressed that a range of combinations should be tried to ensure the worst impact is determined.

Table D1 provides the calculated values for CFrp for 4 return periods for each of the 4 levels of dependency for tides and rainfall suggested earlier. Table D2 is the same matrix for the 2 levels of dependency suggested for drainage and river systems.

CF_{100}	JRP	CFrp
2	20	2
2	50	2
2	100	2
2	200	2
2	500	2
20	20	14.04
20	50	17.17
20	100	20
20	200	23.29
20	500	28.49
100	20	54.82
100	50	77.19
100	100	100
100	200	129.55
100	500	182.43
500	20	214.03
500	50	346.95
500	100	500
500	200	720.57
500	500	1168.08

Table D1 Correlation Function values for Joint Return Periods and Levels of Dependency – Tides and Rivers or Drainage systems

CF_{100}	JRP	CFrp
2	20	2
2	50	2
2	100	2
2	200	2
20	20	12.94
20	50	16.58
20	100	20
20	200	24.12
170	20	73.43
170	50	118.42
170	100	170
170	200	244.04
400	20	146.98
400	50	259.89
400	100	400
400	200	615.63

Table D2 Correlation Function Values for Joint Return Periods and Levels of Dependency – Drainage and Rivers

Assuming that either a precautionary position is taken with regards to the level of dependency by selecting “well correlated” or the more likely “modestly correlated” is used for tidal assessment, Table D3 shows the combination of events which meet the 20, 50, 100, 200 and 500 year return periods. Table D4 provides a similar combination of events for drainage and river flow using higher correlation levels of joint event occurrence. Clearly in applying these combinations appropriate rounding up or down would be done to use the nearest appropriately sized event.

Joint return period	**20 year**	**50 year**	**100 year**	**200 year**	**500 year**
Modestly correlated (20)	CFrp=14.04	CFrp=17.17	CFrp=20	CFrp=23.29	CFrp=28.49
Event combination 1	5, 0.08	5, 0.24	5, 0.6	5, 1.32	5, 4
Event combination 2	2, 0.2	2, 0.6	2, 1.4	2, 3.3	2, 10
Event combination 3	1, 0.4	1, 1.2	1, 2.8	1, 6.6	1, 20
Event combination 4	0.5, 0.8	0.5, 2.4	0.5, 6	0.5, 13.2	0.5, 40
Well correlated (100)	CFrp=54.82	CFrp=77.19	CFrp=100	CFrp=129.55	CFrp=182.43
Event combination 1	5, 0.3	5, 1.1	5, 2.8	5, 7.3	5, 25.8
Event combination 2	2, 0.8	2, 2.7	2, 7	2, 18.5	2, 64.5
Event combination 3	1, 1.6	1, 5.5	1, 14	1, 37	1, 129
Event combination 4	0.5, 3	0.5, 11	0.5, 28	0.5, 74	0.5, 258

Table D3 Combination of Tide and Rainfall Return Periods for Joint Probability Analysis

Joint return period	**20 year**	**50 year**	**100 year**	**200 year**
Strongly correlated (170)	CFrp=73.43	CFrp=118.42	CFrp=170	CFrp=244.04
Event combination 1	5, 0.4	5, 1.7	5, 4.8	5, 13.8
Event combination 2	2, 1	2, 4.2	2, 12	2, 34.5
Event combination 3	0.5, 4	1, 8.4	1, 24	1, 69
Event combination 4	0.2, 10	0.5, 16.8	0.5, 48	0.5, 138
Very strongly correlated (400)	CFrp=146.98	CFrp=259.89	CFrp=400	CFrp=615.63
Event combination 1	5, 0.85	5, 3.7	5, 11.3	5, 34.8
Event combination 2	2, 2.1	2, 9.2	2, 28.3	2, 87
Event combination 3	1, 4.2	1, 18.4	1, 56.6	1, 174
Event combination 4	0.5, 8.4	0.5, 36.8	0.5, 113.2	0.5, 348.5

Table D4 Combination of River and Drainage Return Periods for Joint Probability Analysis

D.4 ASSUMPTIONS AND POINTS TO NOTE

The desk study approach includes a number of assumptions discussed below.

Extreme rainfall and extreme sea level are assumed to be known precisely, so any normal allowances for uncertainty in these variables should be carried through to the use of joint probability results in structural calculations.

A simple linear form is assumed for dependence, as it is unlikely that any better information will be available.

For convenience, probabilities are derived for joint exceedence combinations of high rainfall and high sea level. The return period of the associated response, for example tide-locking of a drainage system will typically only be half as much. This assumption is therefore non-conservative by a factor of around two in terms of return period.

The assumption that conditions at high water are independent of those at the previous high water is also slightly non-conservative, as a single storm or series of high spring tides may continue to have an impact over two or three consecutive high waters.

The assumption that the extreme short-duration rainfall will necessarily occur at high water (not low water or mid-tide) is conservative by a factor of around four in terms of return period (peak tide lasting 3 hours), slightly more than offsetting the two previous non-conservative assumptions. Thus, joint exceedence return period is not the same as the return period of the response, but taking all the simplifying assumptions together the method is considered to be a reasonable approximation of the probabilities.

Where the procedure is applied to rivers and drowned locked outfalls, seasonal effects and durations of flood levels would affect the return period calculation. In principle the method still applies, but as rivers (particularly short rivers) would be responding in a similar manner to drainage systems discharging into them, the level of dependency is be significantly greater.

Where rivers, tides and drainage systems all interact, the complexity of the analysis is increased. It is unlikely that there are many locations where a pragmatic view would not be justified compared to a detailed statistical study. In this situation, considerable amounts of data would be needed to provide an effective analysis.

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GREATER DUBLIN STRATEGIC DRAINAGE STUDY

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