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Simulated future development of the Greater Dublin Area: consequences for protected areas and coastal flooding risk

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Abstract
The Greater Dublin Area (GDA) has experienced rapid urban expansion over the past 20 years. The development pattern has been described as economically driven and developer-led. These changes have had some well recognised consequences such as urban sprawl, congestion and a decrease in environmental quality. Despite the economic downturn, it is projected that the population of the GDA will continue to increase, potentially exacerbating the negative consequences of urban expansion. The objective of this study was to assess the consequences of continued urban expansion on the region, with particular emphasis on protected areas and flooding risk.

To assess the consequences of continued urban expansion we used the MOLAND model; a cellular automaton-based spatial decision support system that has been widely applied across Europe. This model allows the user to explore urban growth under different population, infrastructure and policy scenarios. Using MOLAND we simulated urban expansion in the GDA under four population projections to 2026, assuming spatial trends of urban development stay similar to the recent past. In all scenarios development disperses widely across the study area, formerly separate towns merge and coastal regions are subject to particularly high growth. We discuss the simulated development in terms of its ecological, environmental, social and health effects.

Introduction
Ireland has undergone massive changes over the past three decades: recession in the 1980s, boom in the 1990s and economic collapse at the end of the 2000s (Bartley and Kitchin, 2007). Over this period there have been substantial land-use changes and increases in population. The Greater Dublin Area (GDA) has been the focus of much of this change (Williams et al., 2007). The built fabric of the city of Dublin increased by 9,569 hectares while built fabric within the entire GDA increased by 26,287 hectares over this time period (McInerney and Walsh, 2009). Land use change in the GDA was driven by population growth and economic development, as well as house type and price. With house prices rising within the city, the rural fringes of the city, where it was cheaper to buy or build a house, attracted a growing number of people (Mitchell, 2004). At the fringes of the city, individuals could acquire houses in open countryside while retaining the benefits of the proximity to the capital or other urban areas. A planning regime that imposed few constraints on the conversion of agricultural areas to low-density housing areas facilitated this realisation. Nearby rural towns and villages
grew and merged with Dublin city as urban–rural migration continued, with growth radiating outward along the lines of road and rail transport links (Williams et al., 2007).

Such a massive and rapid expansion of the city has had several well publicised consequences: loss of urban green space, increased ecological pressure on sites of importance, traffic congestion and increased stress, to name but a few (Stapleton et al., 2000, O’Regan and Buckley, 2003, European Environment Agency, 2006, Brennan et al., 2009). These undesirable consequences have lead to the introduction of new planning legislation (Dublin and Mid-East Regional Authorities, 2004, Government of Ireland, 2009b) in an attempt to direct development toward more sustainable patterns. The desired goal of spatial planning policies at national and regional level has been to promote consolidation of the GDA, thereby facilitating a shift from private to public transport, reducing environmental and socio-economic impacts associated with car dependency and traffic congestion (Department of Arts Heritage Gaeltacht and the Islands, 2002, Dublin and Mid-East Regional Authorities, 2004, McInerney and Walsh, 2009). Such an integrated view of planning policy is often hindered by a lack of available spatial information and the necessary tools to address multiple development goals simultaneously (Seder et al., 2000). Developing such tools may alleviate pressures that have lead to significant divergence between spatial planning policy and practice in the past (MacLaran and Williams, 2003, Scott et al., 2006). In addition, it may allow improvement of spatial planning with regards to aspects that have so far been neglected, such as the conservation of natural heritage (Clerkin, 2002) and the prevention of flooding.

There is considerable uncertainty concerning Dublin’s continued growth into the future (Department of Environment and Local Government, 2002, Convery et al., 2006). The Central Statistic Office (CSO) has produced a range of population projections for the region over the period 2011-2026, all of them forecasting a rise in population to a greater or lesser extent (www.cso.ie).

Since the rapid economic development and land-use change of the past has had lasting impacts on the quality of life and environment of the city (Brereton et al., 2008), it would be useful to forecast development into the future, expose potential issues before they occur and structure policy accordingly. Urban growth has been successfully modelled using cellular automaton-based models that incorporate real-world spatial information (White and Engelen 2000). Indeed, this approach has been used in other cities both within Ireland and abroad to evaluate alternative policy scenarios, highlight potential antagonism between continued urban expansion versus limited water resources, and illustrate that urban centres can grow while valuable land-uses, such as agriculture, can be retained (He et al., 2006, Browne et al., 2009, Rafiee et al., 2009).

The MOLAND model is a spatial decision support system widely applied since 1998 at urban/ regional scale (Barredo and Demicheli, 2003, McCormick, 2003, Lavalle et al., 2004, Lavalle et al., 2005, Convery et al., 2006, Petrov et al., 2009). MOLAND allows a user to construct a spectrum of future development scenarios, taking into consideration varying levels of economic, population and policy regimes.

In this paper we have constructed four future scenarios based on regional population projections provide by the CSO, where we explore how the GDA may develop if the current development trends continue. This paper will provide summary statistics of the simulated
land-use in 2026 in each scenario and discuss the corresponding implications for protected areas and flooding risk.

**Methodology:**

**The MOLAND model:**

The MOLAND spatial decision support system comprises two sub-models working at different spatial scales. At the regional scale (macro scale), the model takes as inputs the population and the economic activity (number of jobs by sector) in a region. The model then splits this population and economic activity between the sub-regions encapsulated in the model area. In the Greater Dublin Area (GDA) application, the sub-regions are the administrative counties within the region (Louth, Meath, Kildare, Wicklow, Dublin). At the local scale (micro scale), the demand for housing (based on population estimates) and economic activities is translated into a number of land uses. For example, housing will be provided within residential land use types and economic activity is linked to commercial and industrial land use types (e.g. offices buildings, shopping centres, etc.). The land use type assigned to any given cell is determined by an algorithm which aims to satisfy the demands for land use in each time step (Engelen et al., 2007).

At the regional level, the split of population and economic activity into sub-regions is based on the past relative importance of each sub-region for accommodating population and on job data, including place of work and distance travelled to work. Most of these data for GDA were obtained from CSO Census 1991, 1996, 2002 and 2006 datasets (Shahumyan et al., 2009a).

At the local level, the spatial allocation of land use is modelled by a cellular automaton algorithm. The area modelled is represented as a mosaic of grid cells of 4ha each (200m on the side). Together they constitute the land use pattern of the area. Land use is classified in 24 categories for GDA, eight of which are land use functions (e.g. residential, commercial, etc.), seven are vacant land uses (e.g. arable land, pasture, etc) and nine are land use features (e.g. restricted areas, airports, etc.). This model is driven by the demand for land per region generated at the regional level. Four elements determine whether a piece of land (each 4 hectare cell) is allocated to a particular land use or not:

- The accessibility of the cell, calculated based on a input map consisting of the transport network;
- Physical suitability of the cell, determined by the topographic and environmental appropriateness of cell to support a particular land use and associated activity;
- Zoning status or institutional suitability (e.g. legal constraints);
- The quality of the neighbourhood of the cell, which consists of a circular area with a radius of eight cells. For each land use a set of user-defined rules determines the degree to which it is attracted to, or repelled by, the other land uses present in the neighbourhood.

Based on these elements, the micro model calculates for every simulation step (typically one year) the transition potential for each cell for each land use type (White and Engelen, 2000). In the course of time, and until regional demands are satisfied, cells will change to the land...
use for which they have the highest potential. Further details of the MOLAND model can be found elsewhere (Barredo et al., 2003).

Calibration is achieved by running simulations over a known historical period (in this case 2000–2006). The simulations are initiated using the historical dataset (2000) in order to test the simulation results using the reference dataset (2006). Subsequently the simulations are validated by running the model forward (to 2050) and checking the consistency of the resulting map. The future simulation of land-use can then be performed using the parameters of the already calibrated model, assuming, however, that the calibrated factors will remain relatively stable during the studied period. Detailed description of the calibration technique and used datasets for GDA is presented in a separate paper (Shahumyan et al., 2009a).

Population projections:

The national projections included three international migration (M0, M1, M2) assumptions and two fertility (F1, F2) assumptions, giving a total of six scenarios; M1F1, M1F2, M2F1, M2F2, M0F1 and M0F2. Of these, the regional projections for the eight Regional Authorities only considered M2F1 and M0F1. When coupled with the two internal migration scenarios the regional projections included four scenarios; M2F1 Recent (M2F1R), M2F1 Traditional (M2F1T), M0F1 Traditional (M0F1T), M0F1 Recent (M0F1R).

Projection assumptions:
M2 assumes an annual net inward international migration of 21,400 to the region in the period, while M0 assumes zero annual net inward migration. F1 assumes the total fertility rate to remain at its 2006 level of 1.9 for the lifetime of the projections. The internal migration scenarios, 'Recent' and 'Traditional', were developed due to differences found between censuses carried out up to 1996 versus the 2002 and 2006 censuses. The 1996 and pre-1996 censuses reveal a fairly stable picture in terms of the magnitudes of the inward, outward and net migration flows, with the Dublin and Mid-East regions receiving positive net migration flows while all other regions had negative flows. This flow pattern was reversed in the 2002 and 2006 censuses. Due to the lack of stability in internal migration movements over the period 1996 to 2006 the two internal migration scenarios were formulated. ‘Recent’ assumes we apply the patterns observed in 2002 and 2006 up to 2026, while under ‘Traditional’, the 1996 pattern of inter-regional flows is applied in 2016 and kept constant thereafter, with the difference between the 2006 and 1996 patterns apportioned over the years between 2006 and 2016.

Greater Dublin Area (GDA) versus MOLAND study area:
The GDA, comprising the Mid-East region and the Dublin region, is of similar, though not identical, extent to the MOLAND study area named Greater Dublin Region (GDR). The GDA consists of the Dublin counties, Meath, Kildare and Wicklow. The GDR consists of the Dublin counties, Meath, Kildare, Wicklow and Louth. Thus it was necessary to estimate the population for Louth in 2026 and add it to projected GDA population in 2026.
Louth’s population in 2006 was known from CSO data to be 111,267 people. To estimate Louth’s population in 2026 under each scenario we used the formula:

\[
\text{2026 population} = \left(\frac{\text{Border region 2026 population}}{\text{Border region population 2006}}\right) \times (\text{Louth 2006 population})
\]

The resulting values for each scenario were added to the corresponding GDA population projections (Table 1).

**Table 1. Projected populations in the GDR by 2026 under the four regional population projections**

<table>
<thead>
<tr>
<th></th>
<th>2026 M2F1T</th>
<th>2026 M2F1R</th>
<th>2026 M0F1T</th>
<th>2026 M0F1R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Border 2026 population</td>
<td>592,000</td>
<td>651,000</td>
<td>523,000</td>
<td>575,000</td>
</tr>
<tr>
<td>Louth Multiplier</td>
<td>1.26</td>
<td>1.39</td>
<td>1.11</td>
<td>1.22</td>
</tr>
<tr>
<td>Louth 2026 population</td>
<td>140,149</td>
<td>154,117</td>
<td>123,814</td>
<td>136,125</td>
</tr>
<tr>
<td>GDA 2026 population</td>
<td>2,413,000</td>
<td>2,195,000</td>
<td>2,010,000</td>
<td>1,816,000</td>
</tr>
<tr>
<td>GDR 2026 population</td>
<td>2,553,149</td>
<td>2,349,117</td>
<td>2,133,814</td>
<td>1,952,125</td>
</tr>
</tbody>
</table>

**Table 2: Cell numbers and mean population density within Urban Land Use Types for Calibration**

<table>
<thead>
<tr>
<th>County</th>
<th>Residential Class</th>
<th>Cell number</th>
<th>Mean Population Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louth</td>
<td>Continuous Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Medium Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>212</td>
<td>265</td>
</tr>
<tr>
<td></td>
<td>Discontinuous Sparse</td>
<td>273</td>
<td>336</td>
</tr>
<tr>
<td>Meath</td>
<td>Continuous Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Medium Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>149</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>Discontinuous Sparse</td>
<td>414</td>
<td>414</td>
</tr>
<tr>
<td>Dublin</td>
<td>Continuous Dense</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Medium Dense</td>
<td>65</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>3,511</td>
<td>3,925</td>
</tr>
<tr>
<td></td>
<td>Discontinuous Sparse</td>
<td>405</td>
<td>481</td>
</tr>
<tr>
<td>Kildare</td>
<td>Continuous Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Medium Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>247</td>
<td>405</td>
</tr>
<tr>
<td></td>
<td>Discontinuous Sparse</td>
<td>394</td>
<td>526</td>
</tr>
<tr>
<td>Wicklow</td>
<td>Continuous Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Medium Dense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>214</td>
<td>267</td>
</tr>
<tr>
<td></td>
<td>Discontinuous Sparse</td>
<td>388</td>
<td>486</td>
</tr>
</tbody>
</table>
Estimating population share per residential class:

There are four residential land use classes, namely Continuous Dense, Medium Dense, Discontinuous and Discontinuous Sparse, used in the current land use map in the MOLAND model (Engelen et al., 2004). However, in the Greater Dublin Region the majority of population is concentrated in discontinuous and discontinuous sparse land use categories. To increase the accuracy of the model we split the population into two groups: ‘Sparse’, which includes discontinuous sparse urban fabric, and ‘Other’ which includes the remaining three categories. To estimate the share of the population in each class on a per county basis we used population densities in sample Electoral Districts (EDs) from each county. The EDs were sampled only if the relevant residential class was the sole residential class within the ED and was present in all three time periods of model calibration (1990, 2000 and 2006). Population densities were calculated using the mean value of the sample of EDs.

The population present in the two groups was calculated based on cell number and density values for each county using the following formulae:

Sparse Population = Density Sparse * Sparse Cell Number

Other Population = Total population – Sparse population

| Table 3: Residential populations within urban land use types for the calibration period |
|------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|------------------------------------------|------------------|------------------|------------------|------------------|------------------|
| Louth | 37,783 | 35,170 | 38,661 | 53,158 | 63,433 | 72,606 |
| Meath | 76,552 | 83,093 | 83,334 | 28,521 | 42,821 | 79,497 |
| Dublin | 61,290 | 62,358 | 56,826 | 963,243 | 1,038,444 | 1,130,350 |
| Kildare | 47,783 | 60,570 | 85,581 | 73,591 | 93,724 | 100,754 |
| Wicklow | 55,193 | 59,525 | 72,391 | 41,527 | 51,154 | 53,803 |

The population of the two groups in the projected year 2026 was calculated as follows:


Other Population 2026 = Projected population 2026 – Sparse population 2026

When calculating the effect of population growth on land use in the Greater Dublin Region we therefore assumed that current population density will be maintained, i.e. there is little ‘infilling’ and/ or high density urban development.
Employment Projections:
Employment data is divided into three broad categories in MOLAND: Industrial, Commercial and Services. It should be noted that this employment data should ideally be by place of work (POW) and not by place of residence (POR). In Ireland, place of work data has only been made available for 2002 and 2006, when Sample of Anonymised Records (POWSAR) and Census of Anonymised Records (POWCAR) were implemented. Prior to this censuses recorded employment data by place of residence.

Since POW employment data was available for only one of the model calibration time periods (2006) it was necessary to estimate POW employment data for the other two periods.

POW employment data for 2000 was calculated using the 2002 census which contained both POR, and POW employment data and the 1996 census which contained only POR employment data. The proportion of jobs in each sector per county was calculated using the formulae:

\[
\frac{\text{POR 2002}}{\text{POW 2002}} = \text{POW coefficient}
\]

\[
\frac{\text{POR 1996}}{\text{Unknown POW 1996}} = \text{POW coefficient}
\]

\[
\Rightarrow \text{Unknown POW 1996} = \frac{\text{POR 1996}}{\text{POW coefficient}}
\]

Assumption: POW coefficient remains unchanged between 2002 and 1996.

\[
\frac{(\text{POW 2002} - \text{POW 1996})}{6} = \text{Yearly increase of POW}
\]

\[
\text{POW 2000} = \text{POW 2002} - 2\times(\text{Yearly increase of POW})
\]

POW employment data for 1990 was calculated by a similar process using the 1996 and 1991 censuses.

POW employment data for 2026 was estimated using an annual linear growth rate:

\[
\text{POW 2026} = \text{POW 2006} + 20\times(\text{POW 2006} - \text{POW 2000})/6
\]

The employment data was projected for 2026 M2F1 traditional scenario at first. Then taking into account population ratios between different scenarios the other three cases were estimated:

\[
\text{Employment 2026 other} = \text{Employment 2026 M2F1 traditional} \times \frac{\text{Population 2026 other}}{\text{Population 2026 M2F1 traditional}}
\]

The final data used in MOLAND for the current research is presented in Table 4.
Table 4: Data used in MOLAND for the 2026 scenarios simulation

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2006</th>
<th>2026 Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated</td>
<td>POWCAR</td>
<td>M0F1R</td>
</tr>
<tr>
<td>Population (total)</td>
<td>1,590,790</td>
<td>1,773,803</td>
<td>1,952,125</td>
</tr>
<tr>
<td>Population (other)</td>
<td>1,289,575</td>
<td>1,437,010</td>
<td>1,581,474</td>
</tr>
<tr>
<td>Population (sparse)</td>
<td>301,215</td>
<td>336,793</td>
<td>370,651</td>
</tr>
<tr>
<td>Industry</td>
<td>223,494</td>
<td>259,800</td>
<td>290,984</td>
</tr>
<tr>
<td>Commerce</td>
<td>250,386</td>
<td>321,790</td>
<td>427,805</td>
</tr>
<tr>
<td>Services</td>
<td>166,673</td>
<td>211,656</td>
<td>161,831</td>
</tr>
</tbody>
</table>

Scenario outputs:
Each scenario represented a distinct end point along a spectrum of population growth. In order of increasing 2026 projected population the scenarios are M0F1R, M0F1T, M2F1R and M2F1T. M0F1R represents the lowest projected population of 1,952,125, with the projected populations of M0F1T, M2F1R and M2F1T containing approximately 200,000, 400,000 and 600,000 more people respectively. MOLAND simulated 2026 maps for each scenario were exported to ArcGIS system in raster format. Cell counts for each landuse type were calculated using the Hawth’s tools free extension for ArcGIS (http://www.spatialecology.com/) and then tabulated in MS Excel. For ease of data handling the cell counts were aggregated into three classes; *Agriculture*, *Semi-natural and green urban*, and *Built*. Cell counts were converted to an area value in hectares by multiplying by 4. The outputs from the four scenarios were contrasted in MS Excel.

GIS analysis of scenario outputs:
Since raw area values alone, even when compared on a county by county basis, are not greatly informative output maps for each scenario were examined using GIS to visualise the forecasted 2026 landuse patterns and to identify areas of landuse change between 2006 and differences between scenarios.

Protected areas:
A GIS layer containing the locations of all legally protected sites (National Heritage Areas (NHAs), Special Areas of Conservation (SACs) and Special Protected Areas (SPAs)) and sites proposed for protection (proposed NHAs (pNHAs)) was overlaid on the scenario maps. To identify which sites would be threatened and quantify the impact of forecasted development a 1km buffer was created around the protected areas and cell counts for each landuse type within this buffer were calculated, aggregated and converted to area values as above.

Coastal Development:
When the scenario outputs were first viewed, coastal areas seemed to be forecast for particularly heavy development. To investigate this further a 2km coastal buffer was created. Cell counts for each landuse type within this buffer were calculated, aggregated and converted to area values as above. The buffer outputs from the four scenarios were contrasted in MS Excel. The number and type of protected areas within this buffer were found. The flooding...
Simulated future development of the Greater Dublin Area

history of coastal towns which were forecast to experience pronounced development were reviewed using the Office of Public Works (OPW) National Flood Hazard Mapping website (http://www.floodmaps.ie).

Results:

Changes in landuse share:
As would be expected development was greatest in the scenarios which had the highest 2026 populations. New Built was generated primarily from the conversion of Agriculture, with Semi-natural and green urban being much less affected. The area of Semi-natural and green urban converted to Built was 1% or less of the area of converted Agriculture in all scenarios. M0F1R has a projected increase in Built landuse area of 18,096 hectares; M0F1T, M2F1R and M2F1T have greater projected increases by approximately 7,000, 14,000 and 21,000 hectares respectively, i.e. for each additional 200,000 people projected to live in the study area by 2026, approximately 7,000 hectares of Agriculture is converted to Built.

Areas with heavy urban development:
Several areas were identified that undergo development in every scenario. Significant expansion occurs in the peripheral towns of Celbridge, Rathcoole, Clonee, Swords and Malahide, a continuation of current trends (Williams and Shiels, 2002). Also of note is the pronounced development around the coastal settlements such as Rush, Balbriggan, Malahide and Portmarnock north of the city and Bray, Greystones and Wicklow south of the city (Figure 2).

In addition to the above, under the M2F1 scenarios an unbroken strip of coastal urban fabric stretches from Malahide in the north to Bray in the south. The towns of Lusk and Rush merge; Swords, Malahide and Portmarnock form a ring of coastal development (Figure 3), encircling a pocket of agricultural land and isolating this area from both the wider countryside and the coast. Also of note is the isolation of the Phoenix Park from the wider countryside. In 2006 this area is connected by the Liffey river valley (Figure 1), under the M2F1 scenarios this area is forecasted to be engulfed by development by 2026.

Impact on protected sites:
The most heavily impacted sites remained constant across all scenarios, these being the Tomnafinnoge Wood, Royal Canal, North Dublin Bay, and Knocksink Wood. Other heavily affected sites include Loughshinny coast, Barmeath Woods, Liffey Valley and Feltrim Hill. Sites with legal protection (NHAs, SPAs & SACs) and non-protected sites of recognised ecological and/or heritage value (pNHAs) were also affected (Table 5).
Figure 1. Landuse in the GDR in 2006. The Liffey river valley is circled.
Figure 2. Forecast landuse in the GDR in 2026 under the M0F1R (left) and M0F1T scenarios (right). Note the expansion of Rathcoole, Celbridge, Clonee and Rush, and the merger of Swords and Malahide.

Figure 3. Forecast landuse in the GDR in 2026 under the M2F1R (left) and M2F1T scenarios (right). Areas isolated from the wider countryside by development are circled.
Table 5. Protected sites forecasted as impacted by development. The area of vegetated land lost in hectares (ha) within 1km of the sites is listed by scenario.

<table>
<thead>
<tr>
<th>Site name</th>
<th>Designation</th>
<th>M0F1R</th>
<th>M0F1T</th>
<th>M2F1R</th>
<th>M2F1T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomnafinnoge Wood</td>
<td>SAC</td>
<td>-632</td>
<td>-784</td>
<td>-900</td>
<td>-1204</td>
</tr>
<tr>
<td>Royal Canal</td>
<td>pNHA</td>
<td>-452</td>
<td>-592</td>
<td>-1084</td>
<td>-1128</td>
</tr>
<tr>
<td>North Dublin Bay</td>
<td>pNHA</td>
<td>-112</td>
<td>-408</td>
<td>-612</td>
<td>-900</td>
</tr>
<tr>
<td>Knocksink Wood</td>
<td>pNHA</td>
<td>-200</td>
<td>-404</td>
<td>-460</td>
<td>-592</td>
</tr>
<tr>
<td>Loughshinny Coast</td>
<td>pNHA</td>
<td>-156</td>
<td>-216</td>
<td>-364</td>
<td>-516</td>
</tr>
<tr>
<td>Barrow Valley At Tankardstown Bridge</td>
<td>pNHA</td>
<td>-160</td>
<td>-184</td>
<td>-228</td>
<td>-292</td>
</tr>
<tr>
<td>Kilpatrick Sandhills</td>
<td>SAC</td>
<td>-156</td>
<td>-168</td>
<td>-232</td>
<td>-220</td>
</tr>
<tr>
<td>Liffey Valley</td>
<td>pNHA</td>
<td>-144</td>
<td>-220</td>
<td>-236</td>
<td>-276</td>
</tr>
<tr>
<td>Buckroney-Brittas Dunes And Fen</td>
<td>SAC</td>
<td>-144</td>
<td>-124</td>
<td>-196</td>
<td>-256</td>
</tr>
<tr>
<td>Barmeath Woods</td>
<td>pNHA</td>
<td>-144</td>
<td>-208</td>
<td>-188</td>
<td>-228</td>
</tr>
</tbody>
</table>

Coastal Development:
In 2006 25.6% of land within 2km of the coast consisted of Built. All scenarios forecast an increase in this percentage; Built comprised 30.5%, 32.7%, 35.4% and 37.7% of the 2km buffer in M0F1R, M0F1T, M2F1R and M2F1T respectively. Almost a quarter (24.8%) of all protected sites fell within the coastal buffer, though there were differences between types (Table 6).

Table 6. Number and type of protected sites within 2km coastal buffer.

<table>
<thead>
<tr>
<th>Total within study area</th>
<th>Number within 2km coastal buffer</th>
<th>Percentage within 2km coastal buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPA</td>
<td>44</td>
<td>15</td>
</tr>
<tr>
<td>SAC</td>
<td>83</td>
<td>24</td>
</tr>
<tr>
<td>NHA</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>pNHA</td>
<td>219</td>
<td>48</td>
</tr>
<tr>
<td>Total</td>
<td>351</td>
<td>87</td>
</tr>
</tbody>
</table>

Coastal flooding:
As noted above all scenarios forecast pronounced development around the coastal settlements of Rush, Balbriggan, Malahide, Portmarnock, Bray, Greystones and Wicklow. The OPW have records of flooding in all the areas over a variety of timescales (Table 7.)

Discussion:
This work clearly underlines the need for a change in the spatial planning of development in the Greater Dublin Region. The scenarios presented here explore a continuation of the trends of development within the GDR over the past 16 years (Scott et al., 2006). The results
highlight that if current trends of urban development driven by private interest continue, significant negative environmental effects can be expected. While more pronounced in the M2F1 scenarios, in all scenarios development disperses widely across the study area, formerly separate towns merge and coastal regions are subject to particularly high growth, even though these regions are particularly sensitive to urban development.

**Potential effects of development trends on biodiversity and protected sites:**
The forecasted dispersed development in the GDR would likely result in habitat loss and fragmentation, particularly in the M2F1 scenarios, with all the associated consequences of population isolation, local extinctions and altered community structure (Soulé et al., 1988, Forman and Alexander, 1998, Fernandez-Juricic and Jokimaki, 2001, Fahrig, 2003, Shochat et al., 2006). Areas of ecological importance are forecast to be affected by development in all scenarios (Table 5). Although the importance of these areas are recognised in County Development Plans (Dún Laoghaire Rathdown County Council, 2004, Kildare County Council, 2005, Meath County Council, 2007), the proximate nature of the modelled development means that Local Authorities will have to be vigilant in monitoring and enforcement of regulations and legislation to ensure the integrity of the sites.

Furthermore in all scenarios, but particularly in the M2F1 scenarios, development along the coast is intense. Increased development is simulated to occur adjacent to all coastal protected sites, particularly SPAs. It has been documented that human activity disturbs wildlife in SPAs (Burton et al., 2002a, Burton et al., 2002b, Northern Ireland Executive, 2003, Burton et al., 2006, Holm and Laursen, 2009) and the forecast development would in all likelihood increase disturbance in these areas. Beyond the borders of the protected sites disturbance can be expected to be more intense. Given that the European Court of Justice has already ruled that the Irish Government has already failed to meet its obligations under both the Birds and Habitats Directives (EU Commission v. Ireland, 2010) any increase in disturbance could be expected to incur additional censure from the EU which Ireland can ill afford at present. By identifying sites that may be pressured by future development action can be taken to create appropriate conservation and management plans before development pressure adversely affects these sites.

### Table 7. Flooding events recorded by the OPW

<table>
<thead>
<tr>
<th>Town</th>
<th>Flooding events listed by OPW</th>
<th>Recurring events</th>
<th>Timeframe of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rush</td>
<td>9</td>
<td>4</td>
<td>2000-2004</td>
</tr>
<tr>
<td>Balbriggan</td>
<td>4</td>
<td>1</td>
<td>2000-2002</td>
</tr>
<tr>
<td>Malahide</td>
<td>7</td>
<td>4</td>
<td>2002</td>
</tr>
<tr>
<td>Portmarnock</td>
<td>10</td>
<td>5</td>
<td>1986-2002</td>
</tr>
<tr>
<td>Bray</td>
<td>9</td>
<td>4</td>
<td>1905-2003</td>
</tr>
<tr>
<td>Greystones</td>
<td>6</td>
<td>5</td>
<td>2003</td>
</tr>
<tr>
<td>Wicklow</td>
<td>3</td>
<td>3</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Potential effects of development on ecosystem services:
The dispersed nature of the simulated development in each scenario implies an exacerbation of existing issues. The spread of Built across the region would result in the alteration of soil processes such as decreased carbon (C) sequestration and nitrogen (N) cycling (Lehmann and Stahr, 2007, Tratalos et al., 2007, Lorenz and Lal, 2009). Urban land use planning can help to reduce urbanisation effects on biogeochemical C and N cycles; for example, by limiting disturbance to unproductive urban soils while promoting dense plant cover on productive soils, using permeable/semi-permeable materials to avoid total soil sealing and incorporating green-roofs and living walls to mitigate vegetation loss.

In addition to the soil, dispersed development can be expected to affect the air and water. Dispersed development would necessitate car centric transport for the population (Cervero and Gorham, 1995) leading to increased air and water pollution (Forman and Alexander, 1998). As emissions from road traffic are the primary threat to the quality of air in Ireland (EPA (Environmental Protection Agency), 2004), and as all urban areas are forecast to expand in all scenarios, air quality within urban areas could be expected to degrade, all other things being equal. To mitigate these effects an urban aforestation campaign could be enacted as research suggests urban vegetation can ‘scrub’ the atmosphere of pollutants (Nowak, 2006, Bealey et al., 2007, McDonald et al., 2007, Jim and Chen, 2008).

Wastewater provision over such a dispersed area would be extremely difficult and expensive, necessitating septic tank use in a large number of dwellings. Even though technology is improving, this higher number of tanks can be expected to increase the rates of groundwater contamination (Yates, 1985, Jamieson et al., 2002).

The intense coastal development merits attention for two reasons. Firstly, it is well known that urbanisation within a drainage basin tends to increase the volume of run-off, increase peak discharge and decrease the time taken to reach peak discharge. Many of the coastal areas that undergo intense development within the simulations are on rivers (e.g. Dublin City, Malahide, Balbriggan, Rush, Bray, Wicklow) and have experienced flood events in the recent past. As extreme weather events are predicted to increase globally (Few, 2003) and nationally (Sweeney and Fealey, 2002), care must be taken to ensure that if development does occur, it incorporates effective drainage systems such as protected buffers along river banks, artificial wetlands for water retention and porous pavement materials to reduce run-off (Booth, 1991, Braune and Wood, 1999, Hood et al., 2007).

Secondly, human settlements on coastal areas can influence the effective sea level rise experienced by those areas (Ericson et al., 2006). The particularly high coastal development merits special attention by Regional and Local Authorities to ensure human activities do not exacerbate the effects of global sea level rise (Church and Gregory, 2001). Furthermore, the OPW reports recent flooding in all coastal towns and as sea levels rise these flooding events can be expected to increase (Bosello et al., 2007).

Potential social and health effects of development:
The development simulated here - i.e. dispersing to a greater or lesser degree across the region - represents a continuation of current unfavourable trends (Scott et al., 2006). These trends imply increased isolation of residents within urban centres from the surrounding natural areas and relatively less green space within the urban centres (Brennan et al., 2009). This could lead
to negative social effects, such as increased crime rates, increased stress, decreased physical activity and decreased longevity (Frumkin, 2001, Kuo and Sullivan, 2001, Humpel et al., 2002, De Vries et al., 2003).

The spread of development across the region would make the provision of services and public transport extremely difficult, and while national and regional planning guidelines have been created to attempt to steer development toward a more consolidated, sustainable settlement pattern, these efforts have had mixed results (Scott et al., 2006).

Commuting in the GDA is already a stressful experience (O’ Regan and Buckley, 2003), with time lost due to congestion costing the economy an estimated €640m (DTO (Dublin Transportation Office), 2001). An increase in car dependency implied by the dispersed nature of the forecasts would likely exacerbate the situation. Furthermore, work has already been carried out that suggests that growth in the several areas across GDA will outpace future wastewater treatment provision (Shahumyan et al., 2009b). Similar deficiencies could be expected for other services such as waste disposal, education, health provision and emergency service response time.

**Conclusion:**

While the economic growth fuelling this development pattern was regarded as a boon to the country, the consequences of such rapid and developer-led urban expansion have been widely recognised as unfavourable (Williams and Shiels, 2002, European Environment Agency, 2006, Williams et al., 2007). As shown here, the negative consequences are likely to be exacerbated if the fundamental trends in how the development occurs are not guided in a different direction. With the current economic slow-down there is an opportunity to implement more rigorous planning policy to ensure that planning at national, regional and local levels pursues the same agenda and is implemented effectively. As an aid to cohesive planning, tools such as MOLAND are highly valuable in that they allow users to both visualise the results of differing policy choices, in this case maintenance of the status quo, and add an evidence base to policy decisions that has so far been lacking from Irish planning.

The forthcoming planning bill is a step along this path, in that it requires county development plans to set out a core strategy demonstrating that the development objectives in the development plan are consistent with national and regional development objectives set out in the National Spatial Strategy and regional planning guidelines (Government of Ireland, 2009a). Using MOLAND, or a similar tool, it would be possible to simulate the effects of various county development plans upon the region and highlight issues of conflict between county and regional level plans. If such measures were put in place, it could be hoped that development within the GDR will evolve along a more sustainable path.

**Acknowledgement**
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